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Wide Area Stabilization of Radiological Particulate Contamination

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Executive Summary

The U.S. Environmental Protection Agency in collaboration with the Department of Homeland Security developed radiological decontamination and early phase waste management methods in support of first responders. This work was conducted to study the containment of radiological particle contamination, to develop best practices for gross decontamination and mitigation following a radiological incident, to develop guidance for early phase storage of radiological waste, and based on information gained in the first three work areas, to develop an easy-to-use mobile device application that could be leveraged by first responders for technical information, preparedness activities, and operational use during a response and recovery.

The current study determined the containment technologies that meet the needs for the early phase application responding to a wide area radiological incident. The technologies were initially identified through communication with the stakeholders. Literature search further identified advantages and disadvantages for each of the technologies, which were grouped into tiers based on the time-frame they would be available following a radiological release. Stakeholders then ranked containment technologies in terms of their preference and interest in use and availability. The laboratory and field experiments were conducted to fill the technical gaps of the top ranked technologies. The final part of this study gathered operational information on the selected technologies by conducting a field demonstration.

Stabilization technologies are designed to prevent the spread of particles (such as by resuspension) and are routinely used in industries such as road construction for dust control. The application of rapidly available and easily applied stabilization technologies has the potential for accomplishing multiple goals following the release of radioactive particles from radiological dispersal devices, improvised nuclear devices, or nuclear facility accidents. Preventing or reducing resuspension provides a reduction in inhalation dose to responders. In addition, such technologies would limit the spread of contamination to other non-contaminated, less-contaminated or recently decontaminated areas, subsequently reducing the time and resources needed for decontamination.

Technologies immediately available to first responders include fire hose water and fire-fighting foam. These technologies, while quickly available, contain high water content and therefore may result in decontamination incompatibilities and waste management problems, particularly for soluble radionuclides such as Cesium-137 (Cs-137). More traditional technologies for radionuclide stabilization include those used routinely in the nuclear industry. Such technologies have previously been demonstrated as highly effective, but are difficult to obtain in enough quantities to treat a wide area contamination event during the early phase response following a radiological release.

Interim technologies such as those found at local hardware stores, city or county public works, or state resource facilities offer wider availability in larger quantities, but have not previously been tested for stabilization of radiological particulates. Three examples were selected for additional testing, representing materials that can be quickly and easily applied to large areas using existing equipment and for which experimental data would address technical gaps. Soil$_2$O®[1] dust control

[1] http://www.geltechsolutions.com/soil2o/home.aspx

wetting agent, calcium chloride ($CaCl_2$) salt[2] used in dirt-road dust mitigation, and Phos-Chek®MVP-F[3] fire retardant used to protect structures and create firebreaks in wildland fires were each evaluated. The work presented in this technical report addresses the following technical gaps identified for such materials:

- binding soluble radioactivity and preventing migration
- providing dose reduction
- preventing resuspension of particles (radioactive or surrogate)
- negatively impacting subsequent decontamination efforts and the environment

Experimental evaluations used Cs-137 to determine dose reduction and binding efficacy. The presence of increasing concentrations of $CaCl_2$ demonstrated enhanced sorption of aqueous Cs-137 onto Arizona road dust (ARD), suggesting the transport of soluble contamination would be hindered. The material properties of Phos-Chek®MVP-F fire retardant and Soil$_2$O® wetting agents made separation of aqueous Cs-137 from the solid material extremely difficult. While quantitative data could not be obtained through traditional sorption studies, qualitatively it was determined that Cs-137 was bound to both Soil$_2$O® and Phos-Chek®MVP-F fire retardant.

Cesium-137 was also used to evaluate the dose-attenuation provided by an increasing thickness of stabilization technology. Dose reductions were observed for both Phos-Chek®MVP-F fire retardant resulting in greater than 20x reduction in dose for a 15 millimeters (mm) thickness, and Soil$_2$O® wetting agent resulting in a 13x dose reduction for a 5 mm thickness. Both technologies demonstrated that dose attenuation is affected by drying (and therefore water content). Cesium-137 emits beta radiation and the daughter product emits gamma. It is believed that much of the dose attenuation observed in these studies was from the beta emission. Gamma dose reduction would require a significantly thicker water layer.

Fluorescent particles were used to mimic radioactive contamination in studies to determine resuspension from surfaces during walking and driving over pavers coated with stabilization technologies. Particles were applied to pavers, which subsequently were treated with stabilization technologies, aged outdoors for between 3 and 30 days, and then were impacted by walking and driving activities. The use of fabric swatches on pavers allowed a controlled method of studying transfer of particles from pavers during surface disturbance. Imaging of pavers and fabric swatches was performed under ultraviolet (UV) illumination, and the resulting images were processed to remove background signal noise and to provide an assessment of the area covered by fluorescent particles relative to a specified region of interest for each surface.

The transfer of particles from control pavers (containing no stabilization technology) onto fabric swatches was similar during both walking and driving activities, with a median transfer factor of between 6x and 8x for driving and walking after 14 days of aging, and 1x for both driving and walking after 27 and 30 days of aging respectively. For a shorter aging period of just 3 days, the transfer factor for walking was 3x. Transfer of particles during walking over pavers aged for 3 and 14 days were typically lower than the controls, with Soil$_2$O®, $CaCl_2$ and Phos-Chek®MVP-F fire retardant. During driving activities, the transfer of particles from treated surfaces was least

[2] http://www.tetrachemicals.com/products/calcium_chloride/
[3] http://phoschek.com/product/phos-chek-mvp-f/

for Phos-Chek®MVP-F fire retardant, followed by $Soil_2O$® and greatest for surfaces treated with $CaCl_2$. These results, obtained in Lawrence Livermore facilities are consistent with initial results observed during a demonstration event conducted with Battelle in Columbus, OH earlier in the year. The results for stabilization technologies aged for 27 days with driving, and 30 days with walking were affected by rain events. The results show that the application of stabilization technologies on surfaces can reduce the transfer of particles removed from pavers during walking and driving, provided no rain occurs.

An evaluation of the impacts on decontamination processes, waste generation and the environment following stabilization suggests that while Phos-Chek®MVP-F fire retardant, $CaCl_2$ and $Soil_2O$® bind Cs-137, the material properties of each stabilizer will effect decontamination. Phos-Chek®MVP-F fire retardant dries to form a rubbery material that can easily be removed from surfaces and will contain much of the contamination, providing a positive impact on decontamination processes. The volume of waste generated will depend on the thickness of material applied, and the thickness will be a trade-off with dose reduction requirements. Fire retardant is not considered a hazardous waste and can be disposed of in landfills, but it does have documented toxicity for fish when drainage into populated water occurs. $Soil_2O$® wetting agent dries to form chips and flakes. In experiments containing Cs-137, the flakes were strongly adhered to glass surfaces and were associated with the contamination. While waste volume will be less given the properties on drying, it may also be difficult to remove the flakes from surfaces, potentially making decontamination difficult. $Soil_2O$® wetting agent is also non-hazardous and does not appear to have negative environmental impacts. $CaCl_2$ is not hazardous as supplied, however it forms corrosive brines that may likely leach metals from surfaces, potentially creating hazardous waste without radioactivity and mixed waste with radioactive components. Similarly, the as-supplied material is not a pollutant, but the corrosive brine may leach metals with potential environmental impacts.

In summary, widely available Phos-Chek®MVP-F fire retardant, $Soil_2O$® wetting agent and $CaCl_2$ dust suppression technologies successfully demonstrate the feasibility of using less-traditional materials to stabilize radiological material on surfaces. Additional studies should evaluate the efficacy using technologies appropriate for wide areas (e.g., air-drop, sprayer truck, hose, fast moving vehicles and different types of foot traffic, etc.)

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Acronyms

Abs. RH	absolute relative humidity
ADT	average daily traffic
AFFF	aqueous film-forming foam
APP	ammonium polyphosphate
ARD	Arizona road dust
AS	ammonium sulfate
Atm. Press.	atmospheric pressure
Ba	barium
$CaCl_2$	calcium chloride
CaO	calcium oxide
CERCLA	Comprehensive Environmental Response Compensation and Liability Act
Cs	cesium
Cs_{bound}	sorbed/bound cesium
CsCl	cesium chloride
Cs_{free}	non-sorbed/non-bound cesium
DAP	diammonium phosphate
DHS	U.S. Department of Homeland Security
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FFFP	film-forming fluoroprotein
HCl	hydrochloric acid
HDPE	high-density polyethylene
HPGe	high purity germanium
ID	identification
IND	improvised nuclear device
IR	infrared
Kd	distribution coefficient
Kf	Freundlich sorption constant
LC50	lethal concentration required to kill 50% of specified species
LED	light-emitting diode
LLNL	Lawrence Livermore National Laboratory
MAP	monoammonium phosphate
Mg	magnesium

$MgCl_2$	magnesium chloride
MgO	magnexium oxide
MSDS	material safety data sheets
n	Freundlich sorption order constant
N	sample number
NaCl	sodium choride
NCF	Nuclear Counting Facility
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NPP	nuclear power plant
PFA	pulverized fly ash
PPE	personal protective equipment
QA	quality assurance
QAPP	quality assurance project plan
RCRA	Resource, Conservation and Recovery Act
RDD	radiological dispersal device
ROI	region of interest
SARA	Superfund Amendments and Reauthorization Act
SD, Std. Dev.	standard deviation
Temp	temperature
UV	ultra violet

Units

cm	centimeter
cP	centiPoise
cpm	counts per minute
cy	cubic yard
dpm	disintegrations per minute
fl-oz	fluid-ounce
ft	feet
g	gram
gal	gallon
in	inch
lb	pound
keV	kiloelectron volts
MeV	mega electron Volt
mM	millimolar
mm	millimeter
mPa.s	milliPascal-second
mR/hr	milliRoentgen per hour
m/s	meter per second
t	ton
μCi	microCurie
μL	microliter
μm	micrometer (micron)
W/m^2	Watts per square meter

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1. Introduction

After a radiological dispersion device (RDD) or accidental radiological release, there may be a large area that is contaminated. Re-suspension and tracking of contamination may create issues with containing the contaminated area and create additional exposure to the first responders and later decontamination workers during the early phase response. There is a need for technologies and methodologies to reduce resuspension and tracking. Current radiological particle containment relies on securing the area, setting up a single egress and ingress route, and minimizing the amount of contaminated equipment and vehicles leaving the contaminated zone. The re-suspension and tracking of contamination may greatly hamper the ability to conduct first response activities in that zone, therefore, technologies that can reduce these spreading mechanisms are needed. Nicholson et al. (1989) found that large amounts of fluorescent particles were resuspended due to the turbulence created by a single passing vehicle and that amounts resuspended increased with particle size and vehicle speed. Additionally, radionuclide re-entrainment from rural areas (such as forests) into downstream, populated areas can lead to protracted decontamination efforts. There are several articles documenting the resuspension of radioactive particles released from the Chernobyl nuclear power plant (NPP) in both the vicinity of the reactor (Garger, 1994; Kashparov et al., 1994) and in Europe (Hollander, 1994; Garland and Pomeroy, 1994), as well as, resulting from the Goiania Cs-137 accident (Pires do Rio et al., 1994).

Evaluation of the capture and release of radionuclides in such areas can aid decontamination planning and allow more accurate prediction of fate and transport models. Events in Japan following Fukushima present a unique opportunity to learn and better inform U.S. and international response and recovery planning for future radiological incidents. Improvements in guidance for private citizens and contractors, advanced large area decontamination technologies and large-volume waste treatment technologies can be realized through understanding and learning from current practices in Japan. In most cases in Japan, public self-decontamination guidance and resulting efforts have been derived by trial and error. Incident response and subsequent guidance on stabilization and decontamination in the US can leverage prior efforts to make more informed choices and create a *toolbox* for both decision makers and responders. Similarly, wide area remediation efforts and waste treatment techniques deployed in in Japan following the Fukushima Dai-ichi release can provide input for improved planning the U.S. domestic response.

In the NPP decommissioning industry, coatings are employed to reduce the spread of contained, small-scale contamination. These coatings are not readily available to the first responders and the coatings' applicability in various situations relevant to wide area release (e.g. surface types, applicable area, impact by environmental conditions, etc.) is unknown. First responders may need containment methodologies that can be employed with existing equipment and materials on site using techniques such as fire hosing, street sweepers, and painting.

Desirable properties for potentially successful containment technologies should have the following properties in regard to implementation following a radiological release:

- Ability to suppress particle resuspension and reduce in the spread of contamination
- Ability to reduce dose to responders and public
- Minimize waste consequences when applied and removed

- Long stability and favorable weathering

The study was designed to determine the containment technologies that meet the above listed properties for the early phase application responding to a wide area radiological incident. The technologies were initially identified by the communication with the stakeholders. Literature search further identified advantages and disadvantages for each of the technologies, which were grouped into tiers based on the time-frame they would be available following a radiological release. Twenty-four technologies were identified and recommended by the stakeholders. Since laboratory testing and field-scale evaluations cannot be performed on all technologies, a down-selection of potential stabilization technologies is being performed and is shown in Figure 1-1. Stakeholders including local, state, and federal responders then ranked containment technologies in terms of their preference and availability. This task gathered more information on the stakeholder-selected technologies and identified technical gaps that need to be addressed with experimental research before technical procedures can be developed for containment technology use in the field.

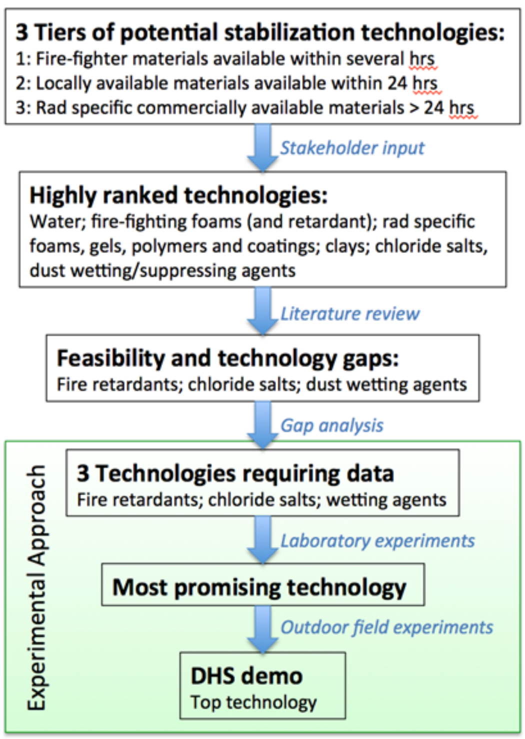

Figure 1-1. Down-Selection Approach

As a starting point for selecting technological for potential investigation, technologies were identified and grouped into one of three tiers based on how quickly they would be available in an appropriate amount (mass or volume, ready for deployment) in response to a wide-area application. The tiers are described in Figure 1-2.

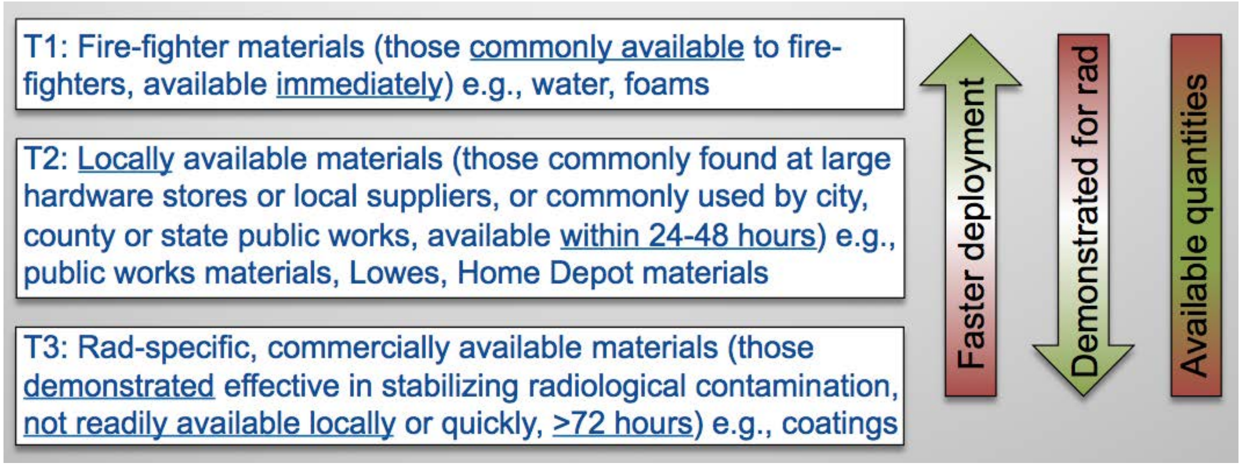

Figure 1-2. Radiological stabilization material tiers for availability

A review by Parra et al. (2009) provided an overview of fixative/stabilization materials, which (together with a literature search for fixatives, stabilizers, wetting agents, fogging, etc.) formed the basis for a list of potential technologies presented at a stakeholder meeting in the initial stages of this work. The 35 meeting participants (stakeholders) represented a wide range of federal, state, and local government, health care professionals, emergency response personnel, and academia. Additionally, the workshop included subject matter expertise from Japan's National Institute for Environmental Studies (NIES). Advantages and disadvantages were identified for each of the technologies, which were grouped into tiers based on the time frame they would be available following a radiological release.

Appendix A summarizes potential containment technologies for use after a radiological release which include a wide range of materials from water to specialized products tested in nuclear facilities. Pros and cons for each material were provided to stakeholders, who were asked for input and any additional information (such as needs, other pros and cons, application techniques, etc.)

2. Selection of Stabilization Materials and Identification of Technical Gaps

Following stakeholder review, the list of containment technologies in Appendix A was evaluated and revised. Median and average scores were calculated from the stakeholder feedback (n=11) with the results shown in Table 2-1. For the purpose of the detailed literature review, technologies with an average stakeholder score greater than 3.00 were evaluated. A dotted line in Table 2-1 separates technologies for review from those that were excluded. Furthermore, epoxy and acrylic type coatings were included and grouped with gels. Additional information was collected from available literature on technologies with an average stakeholder score of 3.00. Specific information included:

- Demonstrated ability to prevent resuspension (Cs-137 contained particulates)
- Impact on ultimate decontamination and waste processes
- Reduction in dose with thickness (dose attenuation)

In some cases, technologies are known to prevent particle migration (e.g., specialized gels and polymers designed to trap and remove contamination). In addition, more specialized technologies may require long production lead times and delivery times, or may not be available in enough quantity to provide wide area stabilization. For this work, the term "wide area" may be considered to be one or multiple city blocks including buildings, streets, grass etc. "Low-tech" containment technologies such as water fogging or fire-fighting foams will be readily and rapidly available. Their ability to prevent resuspension of contaminants is somewhat understood, but they may dissolve and spread contamination rather than serving as containment. Technical gaps for technologies with scores greater than 3.0 require further assessment prior to application in response to a wide area radiological event and are discussed below.

Table 2-1. Stakeholder ranked containment technologies

Technology	Average Score
Water application/ fogging nozzle	3.73
Fire-fighting foam: Wet foam (protein, fluroprotein, aqueous film-forming)	3.55
Gels/polymers/coatings (e.g., *DeconGel, ANL Supergel, Westinghouse WES Strip*)	3.40
Decon foams (e.g., *InstaCote Autofroth, Global Matrechs*, *Inc. NuCap, SNL AFC-380, Allen Vanguard CASCAD and SDF, Dow FrothPak*)	3.50
Clays (e.g., montmorillonite, kaolinite, illite, bentonite)	3.27
Chloride salts ($CaCl_2$, $MgCl_2$ with or without road salt)	3.18
Dry firefighting foam (high expansion e.g., Hi-Ex, Ultra Foam, Jet X)	3.00
Dust wetting agents (e.g., propylene glycol products)	3.00
Rad-Specific Epoxys (e.g., Master Lee *InstaCote CC Epoxy SP InstaCote M-25*)	2.80
Rad-Specific Acrylics (e.g., Master Lee *InstaCote CC Strip, CC Wet and CC Fix; Bartlett Stripcoat TLC and Polymeric Barrier System, Isotron RADblock, ALARA and IsoFix*)	2.90
Commercial Paint	2.27
Dust Surface Crusting Agents (e.g., acrylics)	2.09
Fire-extinguishers: CO_2; Purple K (potassium bicarbonate)	2.00
Mulch	2.00
Gravel	2.00
Dust Binding Agents (e.g., lignin, emulsions)	2.00
Sand	1.73
Cakes (e.g., *AGUA A3000*)	2.10
Lignin	2.00
Imported Soil (non-local, non-contaminated)	1.73
Straw	1.73
Road oil	1.64
Emulsified Petroleum Resins	1.55

Note: high-ranking technologies from stakeholders shown above the dotted line, technologies not selected for further evaluation shown with gray shading.

2.1 Water Application

The application of water, either through a regular hose or a misting nozzle offers rapid deployment by fire fighters. During the response to the Chernobyl incident about 200-300 tons (t) of water per hour was injected into the intact half of the reactor using the auxiliary feed water pumps, but this was stopped after half a day owing to the danger of it flowing into and flooding units 1 and 2.[4] Water is readily available in most areas in a large amount, is the fastest to deploy and is the cheapest technology considered in this evaluation. Water is widely used in dust suppression, from underground mining applications to construction sites and has demonstrated the ability to prevent resuspension by increasing the weight or density of particulates (either through temporary adhesion to surfaces or clumping), or dissolution.

In the case of radionuclide contamination (and those technologies that contain significant quantities of water), we consider two types of representative particles, namely highly soluble Cs-137 from a NPP accident or RDD release, and less soluble improvised nuclear device (IND) debris. For Cs-137, while the use of water spray will significantly reduce the amount of particulate contamination available for resuspension, it will also solubilize the contamination. This may increase difficulty of decontamination with porous materials/surfaces in contact with contaminated water (which subsequently adheres within pores), and clean areas including sewer/drainage systems becoming contaminated. Traditional sources of fire-fighting water may not be available following an IND, but rainfall will leach soluble components of IND debris, and will cause migration of insoluble particles into sewer and drainage systems. Subsequent treatment of large volumes of contaminated water may be required. An alternative would be to deploy absorbent material (e.g., clay boom) to collect contamination prior to runoff into the sewer or drainage system or treatment/filtering of sewer water. There are no technology gaps associated with understanding the application of water as a particulate suppression technology other than site-specific fate/transport and the combination of water and sorbent materials. Because the contaminant ideally remains in place via reducing resuspension, the technology does not purposefully result in dose reduction at the site of initial contamination beyond movement of contamination to drainage areas and away from wide spread surfaces.

2.2 Fire-Fighting Foams and Retardants

Traditionally, fire-fighting foams are designed to starve a fire of oxygen and subsequently dissipate with quick, minimal cleanup. Fire-fighting technologies can be divided between short-term (wet or dry fire-fighting foam) and long-term (fire retardants). Fire retardants were not included in the original evaluation sent to stakeholders, but were recommended by a stakeholder for consideration based on large quantity application and high viscosity. Gross and Hiltz (1980) evaluated foams for mitigating air pollution from hazardous spills; however, the chemicals treated were gases and vapors from solvents rather than particulates.

Foam sprays were used at Chernobyl, although mainly applied to rooms and areas containing flammable materials.[5] Wet, low expansion foam such as aqueous film-forming foam (AFFF),

[4] http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Chernobyl-Accident/

[5] http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Appendices/Chernobyl-Accident---Appendix-1--Sequence-of-Events/

protein-based foams and film-forming fluoroprotein foams (FFFP) are more widely used and carried by fire departments. Their high water content is not amenable to stabilization of soluble contaminants such as Cs-137, which would result in dissolution followed by migration into porous materials and contamination of sewer/drainage systems similar to plain water application (Section 2.1). There may be some interesting behavior to be studied with regard to dissolved cesium cations interacting with anionic surfactants in the foam, but since foam lifetime is designed to be minimal (AFFF dissipation ~ 30 mins, FFFP dissipation ~ 1 hour), the application of such wet foams in the stabilization of Cs-137 is fairly impractical. The nature of foam offers no reduction in whole body ground-shine dose beyond movement of contamination to drainage areas and away from wide spread surfaces.

High-expansion foams (e.g., Hi-Ex, Ultra Foam, Jet X) typically consist of 25-60% water and have an expansion ratio above 200. While the water content is lower than that of low-expansion foams, the likelihood of Cs-137 dissolution and subsequent migration may still be considered problematic. Furthermore, Hi-Ex foam is most commonly used in enclosed locations. The foam can be affected greatly by weather and transit and so outdoor use is limited. It is unlikely the foam offers any dose attenuation from ground-shine.

Long-term fire retardants are most commonly known for their use in wildland/forest fires, often dropped from the air. These materials were suggested by a fire-fighter interviewed during a stakeholder interaction meeting. The retardants are typically dropped in-front of the fire to create a control line or fire break as well as to extinguish fire and can provide protection from days to months. Most are commonly available as a powder that can be mixed in water. The current retardant technologies contain some mixture of monoammonium phosphate (MAP), diammonium phosphate (DAP), ammonium sulfate (AS) and ammonium polyphosphate (APP). A range of viscosities can be achieved by the addition of clay or (more commonly) guar gum as a thickening agent. Examples of Phos-Chek® and Fire-Trol® products are given in Table 2-2. A review by Gimenez et al. (2004) discusses the quality, effectiveness, application and environmental considerations of long-term fire retardants.

Aquatic toxicity of fire retardants due to high ammonium concentrations may present a problem for areas with bodies of water. Additionally, corrosion inhibitors such as sodium dichromate or sodium fluorosilicate may be added, which have human toxicity considerations. The environmental implications of fire-retardant chemicals (including PhosChek® and Fire-Trol® reagents) has been evaluated by Little and Calfee (2002) showing that the presence of ferrocyanide increased the toxicity amongst other factors.

The interaction with contamination (particularly soluble Cs-137) and the ability of long-term fire retardants (such as Phos-Chek® and Fire-Trol® products) to stabilize contamination has not been investigated and represents a technical gap that needs to be addressed before determining whether such technologies are appropriate for application following a RDD/IND. Additionally, the effect of dose attenuation with retardant thickness merits evaluation. The application of fire retardants in a short timeframe may only be feasible in areas that have such wildfire resources, or where retardants could be flown to the area in a rapid timeframe.

The high viscosity (similar to honey or molasses) of some fire retardants such as Fire-Trol® and Phos-Chek® products may be advantageous on non-horizontal surfaces such as roofs and walls, as well as treating agricultural or forest lands, where resuspension from plants/leaves is a concern. Additionally, the thickening agents used in some fire retardants (guar gum and attapulgus clay) are known to bind contaminants, and in the case of clay (which can also be included in fire retardants as a colorant), specifically binds Cs-137 and other radionuclides (Belfiore et al, 1984).

Table 2-2. Examples of long-term fire retardant products, gum thickened, containing corrosion-inhibitors[6,7]

Product	Type	Yield	Viscosity, cP (or mPa.s)	Specific Weight, lb/gal
Phos-Chek®P100-F	MAP/AP, high viscosity	1t = 2,150 gal	801 – 1,500	8.74
Phos-Chek®MVP-F	MAP/AS medium viscosity, contains flow conditioner	1t = 2,225 gal	401 - 800	8.79
Phos-Chek®LC-95A-R	APP low viscosity	1t = 1,054 gal	75 - 225	8.97
Phos-Chek®259-F	DAP low viscosity non-corrosive to magnesium	1t = 1,869 gal	75 - 250	8.90
Phos-Chek®LV-R and MV-R	MAP/AS, low/medium viscosity, contains stabilizers	1t = 860 gal	75 - 225 / 450 - 750	8.93
Phos-Chek®HV-R and -F	MAP/AS high viscosity, contains stabilizer	1t = 775 - 860 gal	1,000 - 1,600	8.93
Fire-Trol®GTS-R	DAP/AS high viscosity	1t = 1325 gal	1,200 - 1,800	9.07
Fire-Trol®LCA-R, LCG-R, LCA-F	APP low viscosity	1t = 923 - 989 gal	<50	9.07 - 9.13
Fire-Trol®931 (Canada only)	APP low viscosity	1t = 962 gal	<50	9.00
Fire-Trol®300F	DAP/AS high viscosity	1t = 1250 gal	1,200 - 1,800	9.12

Note: For comparison, approximate viscosities (centipoise, cP equivalent to mPa.s) of common liquids are: water: 1 cP, ethylene glycol 15 cP, vegetable oil 40-50 cP, tomato juice 180 cP, maple syrup 400-500 cP, glycerin 650-800 cP, castor oil 1,000 cP, glycerol 1500 cP, honey >2,000 cP, molasses >5,000 cP. 1 cp = 1 mPa.s; monoammonium phosphate (MAP), ammonium Sulfate (AS), diammonium phosphate (DAP), Ammonium polyphosphate (APP).

2.3 Specialized Decon Gels, Polymers and Foams

Gels, polymers and coatings have been designed specifically for use in remediating radiological contamination. In some cases, gels and polymer barriers act as "permanent" isolation, whereas

[6] http://www.fs.fed.us/rm/fire/wfcs/products/index.htm
[7] http://www.fs.fed.us/rm/fire/retardants/current/laqa/psi.htm

others are designed to permanently encapsulate the contamination. Some coatings are "strippable" such as Bartlett's Stripcoat TLC (US EPA, 2008a), Sherwin Williams Alara 1146 (Archibald et al., 1999a/b), Isotron Corp Orion SC (US EPA 2008b), Pentek 604 (Archibald et al. 1999a/b), Westinghouse WES Strip (NEI, 1996) and DeconGel (US EPA, 2011), designed to peel away to remove contamination. Strippable coatings offer stabilization plus a single solid waste stream. An assessment of strippable coatings was performed by Ebadian (1998). Such materials have been widely demonstrated and proven successful in removing a percentage of surface-bound contamination on porous and non-porous surfaces for a variety of contaminants. However, strippable coatings have limited impact on contamination that has penetrated into the porous material, and recent outdoor demonstration of such coatings revealed difficulties in removal (US EPA, 2016), potentially leading to excessive worker effort, costs and dose. Bratskaya et al. (2014) provided evidence of a nanosized selective dust suppression coating containing transition metal ferrocyanides that actively bind Cs in carboxylic latex.

Similarly, specialized foams and chemical treatments for use in decontaminating surfaces containing radiological contamination such as Allen Vanguard's CASCAD and SDF-200 (US EPA, 2013a) and EAI Rad-Release (US EPA, 2013b) have been tested on both horizontal and vertical surfaces. Designed for quick decontamination rather than stabilization for longer periods, such foams are generally accepted to be good at removing surface contamination and even removing sub-surface contamination from porous materials.

Logistically, it may be difficult to obtain and mobilize enough specialized foam, gel or coating depending on the area of outdoor contamination. Shelf-life, cure-time, application lifetime, weathering, and effectiveness for particulate contamination are generally well known for these products and are available from the manufacturers and suppliers.

2.4 Clays and Zeolites

Clay and zeolite materials are well known as strong adsorbers, particularly for Cs-137. Clays are routinely used for stabilizing radioactive and hazardous waste. Lacy (1954) treated a mixed fission product solution with montmorillonite. Biotite, zeolite, heavy clay, sepiolite, kaolinite and bentonite uptake of Cs-137 and other radionuclides have been widely researched and demonstrated by Dyer and Mikhail (1985), Passikallio (1999), Said and Hafez (1999) and Bayulken et al. (2010). The ability of clay to sorb and seal when hydrated has led to their inclusion in engineered barrier designs for many nuclear waste disposal concepts. The role of reactive clay barriers in soil for Cs-137 retention and limiting bioavailability was evaluated by Krumhansl et al. (2000). Approximately 1,800 tons of sand and clay, and 3,200 tons of boron, dolomite and lead were dropped by helicopter on to the burning reactor core of Chernobyl in an effort to extinguish the blaze and limit the release of radioactive particles.[8,9] Vovk et al. (1993) and Ahn et al. (1995) demonstrated decontamination of building surfaces (including those in urban areas affected by Chernobyl) using naturally occurring clays from Korea and Ukraine.

[8] http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Chernobyl-Accident/
[9] http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Appendices/Chernobyl-Accident---Appendix-1--Sequence-of-Events/

Since clays and zeolites have been well demonstrated both in the laboratory and in contaminated areas including Chernobyl, few technical gaps exist. The major questions associated with fielding clays and zeolites as a rapid stabilization technology following a radiological release are whether enough material could be deployed in time and whether radionuclides bound to clay dust could be resuspended. Nevertheless, clay should be considered a prime candidate for stabilization, especially since it also serves as a decontamination technology.

2.5 Chloride Salts

Calcium and magnesium chloride salts are widely used for dust control on non-paved roads, hence their availability, rapid deployment and ease of use are preferential. In fact, calcium chloride has been used to treat roads since the 19th century. Both chemicals are hygroscopic, which helps bind dust/particles to the surface. Performance depends on temperature, relative humidity and traffic, with effectiveness generally lasting 6-12 months (Wisconsin Transportation Information Center, 1997 and Han, 1992). Both technologies can well withstand average daily (ADT) traffic up to 250 vehicles and offer fair protection above 250 vehicles (Han, 1992), where ADT is the average number of vehicles in either direction passing a specific point in a 24-hour period (vehicles per day). Sanders and Addo (1993) report 55% aggregate retention compared to a control for $CaCl_2$ and 77% retention for $MgCl_2$. Satterfield and Ono (1996) observed a 92% dust reduction using a 26% $MgCl_2$ solution applied during street sweeping (US EPA, 2004). Both salts are highly soluble, so precipitation will disturb the surface and reduce effectiveness. There are operational issues associated with chloride salt use, including corrosion and the generation of slippery surfaces. Surfaces must be graded well; therefore, the technology cannot be applied to sloped roofing or vertical surfaces. Magnesium chloride requires temperatures above 70°F, RH above 32% and more material compared to calcium chloride to be effective, but creates a harder surface (Wisconsin Transportation Information Center, 1997).

A report by the US EPA on the ecological impact of land restoration and cleanup (US EPA, 1978) states that chlorides can be applied to large affected areas using standard agricultural or construction equipment, but application is restricted to areas where there is space for the equipment to be used effectively. In addition, the EPA report notes that chlorides offer intermediate durability lasting between 1 to 5 years. In practice however, reapplication is needed after rain or after 6 months. Vegetation recovery requires removal of chloride material and the technology is classified as acceptable as an alternative stabilization method for suburban and coastal regions, but a last resort method for agricultural land (US EPA, 1978).

The application of such salts to address radiological contamination is not new; Tawil and Bold (1983) included chloride salts in their guide to radiation fixatives stating that it has been successfully used by the Reynolds Electrical and Engineering Company at the Nevada Test Site to reduce dust and prevent migration of particulate contamination. However, in the urban environments considered for the current evaluation, the aqueous nature of the chloride application may contribute to solubilization of Cs-137. The high concentration of chloride may depress CsCl solubility, but experiments should be performed to evaluate the effect of $MgCl_2$ and $CaCl_2$ on the mobility of Cs-137 in porous materials. The effectiveness of chloride salts to bind or incorporate Cs-137 (thereby preventing migration or resuspension) has not been investigated and represents a technology gap that should be addressed in determining applicability for RDD and IND response. It is anticipated that dose attenuation will be minimal for chloride salt stabilization, similar to that achieved by a thin layer of water. The chloride cake will dissolve under rain, but some researchers have studied additives such as calcium and magnesium oxides (CaO, MgO), sodium silicate (Wu et al., 2007), pulverized fly ash (PFA) (Salyak et al., 2008) with successful results. The use of such additives to chloride salts is recommended for future stabilization experiments.

2.6 Dust Wetting Agents

Dust wetting agents were originally developed for coal mine dust suppression with applications in subsurface mines, on mining roads and on storage and tailing piles to prevent loss and reduce resuspension (Glanville and Wightman, 1979; Glanville and Haley, 1982 and Zeller, 1983). Dust wetting agents are typically surfactants or organic compounds based on alcohols and diols (e.g., propylene glycol) that alter the interaction of particles and surfaces. Dust wetting agents suffer from the same inherent technical problem when considering Cs-137 stabilization, namely the solubility of Cs in the wetting agent and subsequent implications on the management of containment and waste. In the liquid phase, Cs-137 is likely to migrate into porous materials and enter sewer/drainage systems. However, the role of dust wetting agents on the agglomeration of particulates resulting in the encapsulation of Cs-137 has not been investigated. It is assumed that no dose attenuation can be achieved by using dust wetting agents beyond removal of contaminants from the respirable range. Additionally, Instacote provides a wetting agent (CC Wet)[10] specifically for stabilizing radiological, beryllium, asbestos and other hazardous contaminations, to be applied prior to Instacote CC Fix. A similar product (CC Demo 100)[11] penetrates rubble and soil to form a penetrating protective layer over contaminated demolition debris and may be useful in providing some level of protection from reaerosolization of contaminants outdoors. However, a potential disadvantage of these two products is availability at the incident scene in a short period of time in large enough amounts to treat a wide area.

2.7 High Priority Technical Knowledge Gaps in the Literature

To evaluate the effectiveness of such non-traditional technologies, laboratory and field tests are required to address technical knowledge gaps. The following evaluations were proposed:

- Fire Retardants
    - Laboratory-scale sorption of Cs-137 to high viscosity gum-thickened fire retardants;
    - Laboratory-scale dose attenuation of Cs-137 through high viscosity retardants studying the effect of thickness;
    - Outdoor evaluation of aged fire retardant performance in reducing particulate transfer during driving and walking activities; and
    - Evaluation of impacts to decontamination and waste management.

[10] http://instacote.com/cc-wet.htm
[11] http://instacote.com/cc-demolition.htm

- Chlorides
    - Laboratory-scale sorption changes on coupons contaminated with Cs-137 using chloride salt deposits, specifically examining the role of high chloride concentration on the depression of CsCl solubility
    - Outdoor evaluation of aged chloride performance in reducing particulate contamination transfer during walking and driving activities.

- Wetting Agents
    - Laboratory-scale sorption changes on coupons contaminated with Cs-137 using wetting agents
    - Laboratory-scale dose attenuation of Cs-137 using wetting agents
    - Outdoor evaluation of aged wetting agent performance in reducing particulate transfer during driving and walking activities.

3. Laboratory Testing of Stabilization Materials

3.1 Fire Retardant

Laboratory studies using Cs-137 were undertaken to assess dose attenuation due to fire retardant thickness and sorption experiments were conducted to determine fixation of contamination on fire retardant material.

Initially, to evaluate the behavior of fire retardant in the laboratory, the Phos-Chek®MVP-F powder was mixed with water at a variety of ratios spanning that recommended by the supplier. Generally, the mixture formed a viscous material resembling syrup. Increasing layers of material were qualitatively evaluated. At small thicknesses under ambient conditions, the mixture dried. However, at greater thickness the mixture remained viscous, so thicker portions were heated on a hot-plate to facilitate drying. Once dry, the material had a *rubbery* consistency, with a few opaque precipitates dispersed heterogeneously. Images taken during these early qualitative studies are shown in Figure 3-1.

Figure 3-1. Phos-Chek®MVP-F fire retardant initial qualitative studies with increasing drying (A) through (D)

In dose rate attenuation studies, a 0.465 microCurie (μCi) Cs-137 solution (CsCl in a 0.1 Molar (M) hydrochloric acid [HCl]) was added by stippling in microliter (μL) aliquots to the bottom of a glass dish and dried on a hot-plate. The dose rate and number of radioactive disintegrations emanating from the deposited Cs-137 were measured at a fixed height (92 millimeters [mm]) as a positive control using a Victoreen 451B survey meter and a Ludlum *Model 12* survey ratemeter for beta/gamma detection. Fire retardant material was mixed in a 4 g to 16 ml ratio with water, and added stepwise to the glass dish on top of the Cs-137. The dose and activity of Cs-137 were measured at each step through the deposited fire retardant at the same fixed height. Images taken during the experiments are shown in Figure 3-2, and the results are shown in Table 3-1 and Figure 3-3. The dose reduction factor was determined by dividing the dose rate (milliRoentgen per hour [mR/hr]) emanating from the deposited and unshielded Cs-137 (no fire retardant, Figure 3-2A) by the dose rate measured through each thickness of fire retardant (Figure 3-2D). The results show a 25-times reduction in dose rate after the application of a 20 mm thickness (3/4 inch) of Phos-Chek®MVP-F fire retardant compared to the bare Cs-137 deposited source. Accordingly, the counts per minute decrease, but plateau at approximately 100 cpm

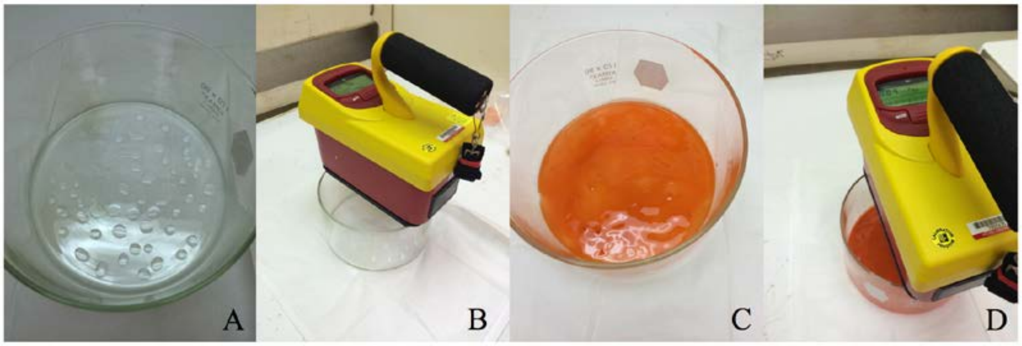

Figure 3-2. Cs-137 Count rate and dose rate attenuation study images

(A) Cs-137 deposited on base of dish; (B) measurement of positive control Cs-137 without Phos-Chek®MVP-F; (C) addition of Phos-Chek®MVP-F; (D) measurement of Cs-137 through Phos-Chek®MVP-F

Cs-137 decays via two parallel paths to metastable Barium-137m (Ba-137m) via emission of a 0.512 Mega electron Volts (MeV) beta particle (94.6%) and to stable Ba-137 via a 1.174 MeV beta particle (5.4%). The meta-stable Ba-137m in the excited state subsequently undergoes further decay through the emission of a 0.662 MeV gamma photon. Consequently, Cs-137 emits both beta and gamma radiation. With the beta slide open, the Victoreen 451B survey meter can detect beta radiation above 0.1 MeV and gamma above 0.007 MeV, so all emissions were detected.

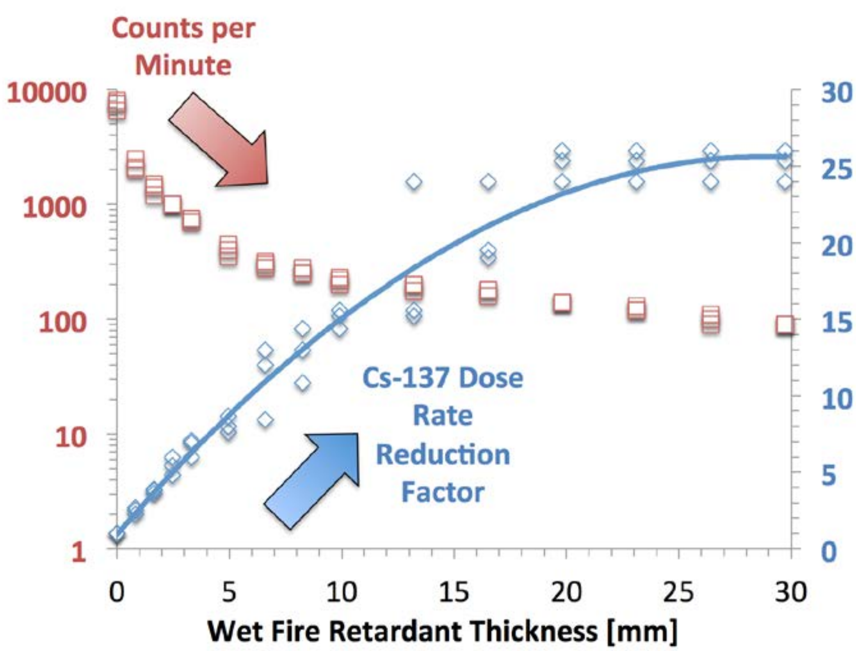

Figure 3-3. Measured Cs-137 count rate and dose rate reduction factor through PhosChek Phos-Chek®MVP-F fire retardant

Table 3-1. Cs-137 measured count rate and dose rate attenuation through wet Phos-Chek®MVP-F fire retardant

Layer	Volume, cm^3	Thickness, mm	Measured counts per minute, cpm					Measured Dose Rate, mR/hr					Dose Rate Reduction Factor				
			Rep1	Rep2	Rep3	Average	SD	Rep1	Rep2	Rep3	Average	SD	Rep1	Rep2	Rep3	Average	SD
0	0	0.00	8000.00	7500.00	6500.00	7333.33	763.76	0.72	0.78	0.76	0.75	0.03	0.00	0.00	0.00	0.00	0.00
1	17	0.83	2100.00	2500.00	2000.00	2200.00	264.58	0.32	0.29	0.30	0.30	0.02	2.25	2.69	2.53	2.49	0.22
2	34	1.65	1200.00	1500.00	1400.00	1366.67	152.75	0.20	0.20	0.20	0.20	0.00	3.60	3.90	3.80	3.77	0.15
3	51	2.48	1000.00	1000.00	1000.00	1000.00	0.00	0.15	0.13	0.14	0.14	0.01	4.80	6.00	5.43	5.41	0.60
4	68	3.30	750.00	750.00	700.00	733.33	28.87	0.12	0.11	0.11	0.11	0.01	6.00	7.09	6.91	6.67	0.58
5	102	4.95	350.00	450.00	400.00	400.00	50.00	0.09	0.09	0.10	0.09	0.01	8.00	8.67	7.60	8.09	0.54
6	136	6.60	280.00	320.00	300.00	300.00	20.00	0.06	0.06	0.09	0.07	0.02	12.00	13.00	8.44	11.15	2.39
7	170	8.26	250.00	280.00	250.00	260.00	17.32	0.05	0.06	0.07	0.06	0.01	14.40	13.00	10.86	12.75	1.78
8	204	9.91	200.00	230.00	220.00	216.67	15.28	0.05	0.05	0.05	0.05	0.00	14.40	15.60	15.20	15.07	0.61
9	272	13.21	175.00	200.00	200.00	191.67	14.43	0.03	0.05	0.05	0.04	0.01	24.00	15.60	15.20	18.27	4.97
10	340	16.51	160.00	180.00	180.00	173.33	11.55	0.03	0.04	0.04	0.04	0.01	24.00	19.50	19.00	20.83	2.75
11	408	19.81	140.00	140.00	140.00	140.00	0.00	0.03	0.03	0.03	0.03	0.00	24.00	26.00	25.33	25.11	1.02
12	476	23.12	120.00	120.00	130.00	123.33	5.77	0.03	0.03	0.03	0.03	0.00	24.00	26.00	25.33	25.11	1.02
13	544	26.42	90.00	100.00	110.00	100.00	10.00	0.03	0.03	0.03	0.03	0.00	24.00	26.00	25.33	25.11	1.02
14	612	29.72	90.00	90.00	90.00	90.00	0.00	0.03	0.03	0.03	0.03	0.00	24.00	26.00	25.33	25.11	1.02

cm^3 = cubic centimeter
cpm= counts per minute
mm = millimeters
mR/hr = milliRoentgen per hour
Rep = replicate
SD = standard deviation

The dose rate reduction appears to be from both the solid material and the water contained in the matrix. This is not surprising since it is likely that the water provided some gamma dose rate reduction and a combination of solid and water matrix provided beta dose rate reduction. It is assumed that the fire retardant retained some water based on the rubbery nature of the dried material, and the thickness of the dried material was not measured or calculated. According to calculations performed (RadProCalculator)[12], a 26.7 cm thickness of water is required to reduce the gamma dose rate from Cs-137 from 1 mR/hr to 0.1 mR/hr (dose rates similar to the two extremes of the dose attenuation measurements). This thickness is an order of magnitude greater than that observed during the laboratory studies. Therefore, it is concluded that the dose rate reduction observed for fire retardant and wetting agent was largely derived from attenuation of beta radiation rather than attenuation of gamma.

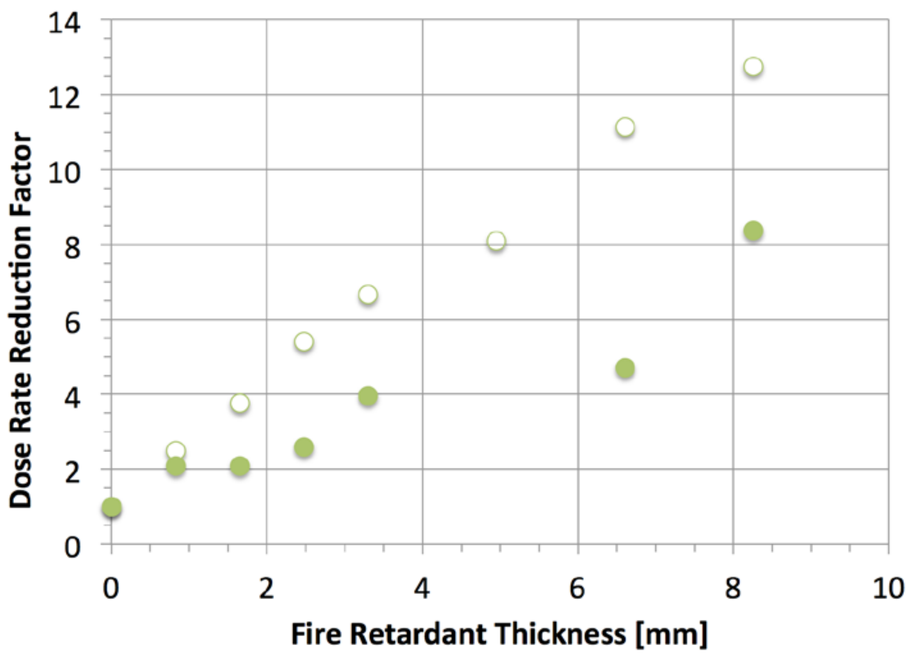

Figure 3-4. Dose rate reduction factors for wet (open circles) and dried layers (full circles) of Phos-Chek®MVP-F fire retardant with Cs-137

Sorption experiments were undertaken to determine the efficacy of Cs-137 binding to Phos-Chek®MVP-F fire retardant. As can be seen in the photographs in Figure 3-1, when Phos-Chek®MVP-F powder is added to water, a viscous material is generated. Despite a variety of methods, liquids could not be filtered from the solid due to the gummy nature of the fire retardant. While this prevented the determination of free (unbound) Cs-137 and calculation of sorption efficiency, it did suggest that leaching of Cs-137 from the fire retardant material would be unlikely or at least slow.

[12] http://www.radprocalculator.com

3.2 Chloride Salts

Because chloride salts are dissolved before application, and applied in a thin layer, no dose rate attenuation studies were commissioned. The binding of Cs-137 onto surfaces using $CaCl_2$ solutions was investigated through sorption studies on Arizona road dust, a National Institute of Standards and Technology (NIST)-traceable particulate material that is well characterized and similar to some material found in urban areas, particularly pertaining to roadways. Calcium chloride was chosen because it is the most commonly used in dirt road stabilization.

Batch sorption experiments were performed to evaluate the sorption behavior of Cs-137 with increasing amounts of Arizona road dust material (nominally 10, 25, 50, 100, 250, 500, 750 and 1000 mg) that were added to individual sample tubes followed by 1 ml of solution containing Cs-137 (nominally 0.155 μCi) and 9 milliliters (ml) of milli-Q deionized water, and varying volumes of 0.333 M $CaCl_2$ and 1 M NaCl up to 1 ml (NaCl being used to provide consistent ionic strength and volume (11 ml total liquid)). Samples were capped, shaken by hand and then placed on an incubating orbital shaker table (Model 3500, VWR) with the temperature set at 25°C. Samples were equilibrated for 4 days before being filtered through a 0.2 micrometer (μm) pore syringe filter. Experiments were performed in triplicate.

The liquid supernatants containing Cs-137 were analyzed at the Lawrence Livermore National Laboratory (LLNL) Nuclear Counting Facility (NCF). The NCF utilizes gamma-ray spectroscopy systems that employ high purity germanium (HPGe) co-axial detectors from ORTEC. Each detector system is comprised of an HPGe detector connected to an ORTEC DSPEC multi-channel analyzer interfaced using ORTEC Maestro PC software for spectral acquisition. Initial calibration of the detectors was accomplished by characterizing the detectors intrinsic efficiency, peak shape parameters, energy linearity and other detector parameters using NIST-traceable point sources that have gamma-ray energies spanning the 0 – 2,000 kiloelectron Volts (keV) energy range. Once the detector had been fully characterized, calibration verification was performed by analyzing NIST-traceable standards of various matrices and geometries (e.g. a point-source, liquid, and soil).

Spectral analysis was performed using LLNL's in-house software code GAMANAL (Gunnick, 1972). The code allows for the automated analysis of gamma-ray spectra collected for a wide array of sample matrices and geometries by using radiation transport physics algorithms to account matrix attenuation and geometry effects.

Samples were prepared for counting by pipetting a known volume (nominally 10 ml) of the Cs-137 bearing solution into high-density polyethylene (HDPE) containers (LLNL-designed "Prindle" vials). These containers' geometry and material are well characterized and designed for use in the LLNL NCF automated sample changer systems. Count times for these samples ranged from 30 min – 90 minutes depending the Cs-137 activity present in the samples. Count times were selected to optimize counting statistics and sample throughput. For these count times, most samples achieved counting uncertainties < 3% for the 661.6 keV gamma peak from Cs-137. Uncertainties reported for the Cs-137 results reflect only the uncertainties on the counting statistics for the 661.6 keV peak. Sorption results are shown in Figure 3-5 and 3-6 for various Arizona road dust to Cs-137 ratios, and for 5 different concentrations of $CaCl_2$ (0, 7.6, 15.1, 22.7 and 30.3 millimolar [mM]), using the equation:

$Cs_{bound} = Kd \times Cs_{free}$

where Cs_{bound} (sorbed/bound cesium) is the activity (disintergrations per minute [dpm]) of Cs-137 bound per gram of Arizona Road Dust (ARD) and Cs_{free} (non-sorbed/non-bound cesium) is the activity of Cs-137 free (unbound) in 1 ml of liquid in equilibrium with the solid phase. A sorption distribution coefficient can be determined either individually (conditional) or as a batch with one changing variable. The average (from triplicate analysis) conditional distribution coefficient (Kd) values (ml/gram [g]) are plotted in Figure 3-5 against the actual mass of Arizona road dust added to each experiment. Here it can be seen that increasing the concentration of $CaCl_2$ results in higher binding of Cs-137, particularly in the presence of higher amounts of Arizona road dust. Optimal binding of Cs-137 is observed when the $CaCl_2$ concentration was highest (30.3 mM) and the mass of Arizona road dust was 750 mg, resulting in a mean conditional Kd value of 5430 ($\sigma = 600$). The results show that Cs-137 binding to road dust can be increased with the addition of chloride salts such as $CaCl_2$.

Additionally, a standard 'linear-type' sorption isotherm plot of the activity (dpm) of Cs-137 sorbed (bound) per gram of Arizona road dust, versus the activity of free (unbound) Cs-137 per ml of solution showed non-linear behavior, suggesting complex equilibrium or kinetic sorption behaviors, which are not unexpected from adsorbent materials and heterogeneous adsorption systems.

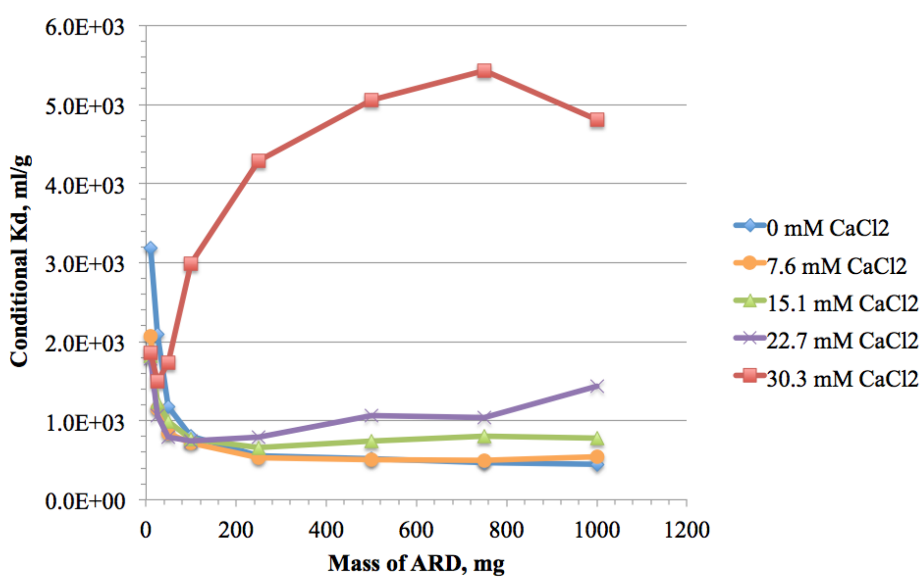

Figure 3-5. Conditional Kd sorption versus mass of Arizona road dust

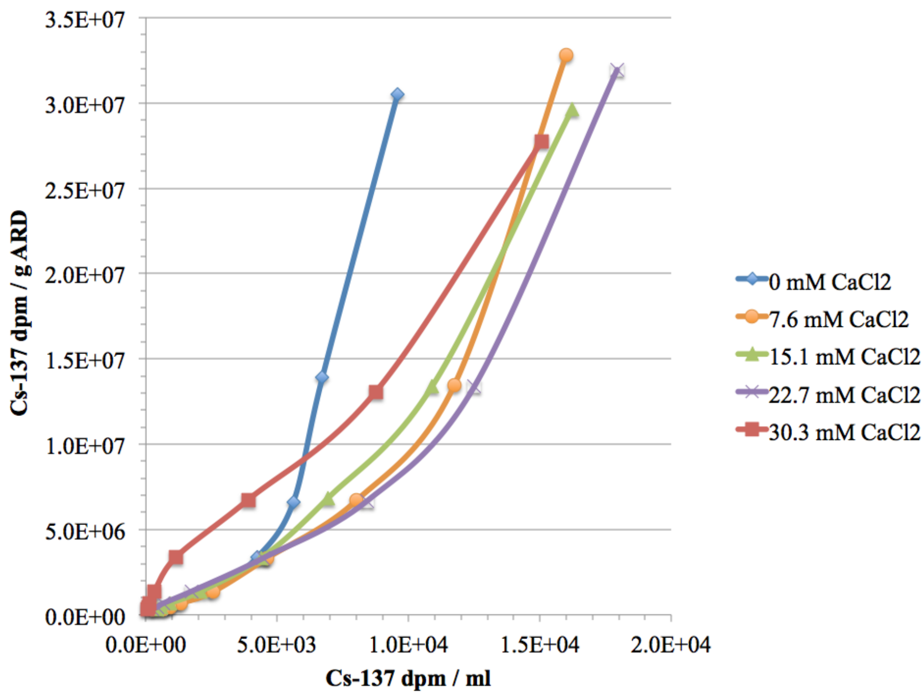

Figure 3-6. Standard sorption isotherm for Cs-137 on Arizona road dust with varying $CaCl_2$ concentrations

Since Arizona road dust includes more than one mineral phase capable of binding Cs, the Freundlich sorption isotherm (Freundlich, 1906) may be a more appropriate model. Such isotherms are applicable to heterogeneous sorption sites and are widely used in quantifying sorption on environmental surfaces, with the sorption-order constant (n) reflecting a measure of non-linearity. Plots are linear and yield both the Freundlich sorption constant, K_f (taken from the intercept on the y-axis) and the sorption order constant, n (taken from the gradient):

$$Cs_{bound} = K_f \times Cs_{free}^{n}$$

The results for each concentration are shown in Figure 3-7 and show that the log of the Freundlich sorption constant (K_f) is proportional to the $CaCl_2$ concentration, as shown in the lower right panel (red). Additionally, the trend in Freundlich sorption-order constant (n) with $CaCl_2$ concentration is shown in the lower right panel (blue), decreasing with increasing $CaCl_2$ concentration. A sorption-order value less than unity indicates that sorption is favorable at $CaCl_2$ concentrations greater than approximately 20 mM (where the interception on the y-axis equals unity). This suggests that $CaCl_2$ concentrations must be kept above approximately 20 mM on surfaces to maintain the positive sorption influence on Cs-137. Rain events will be problematic for $CaCl_2$ deposits as rain will cause dissolution of the chloride salt and will likely lead to the migration of Cs-137 originally stabilized by the salt. Over time, without rain events or wetting, the concentration of $CaCl_2$ will increase due to evaporation. On drying, flakes will be generated, and while Cs-137 may be incorporated into the flakes (potentially hindering migration), it would be desirable to reapply either additional chloride salt solutions or rewet with water. Care must be taken not to apply water in quantities significant enough to lower the $CaCl_2$ concentration below approximately 20 mM.

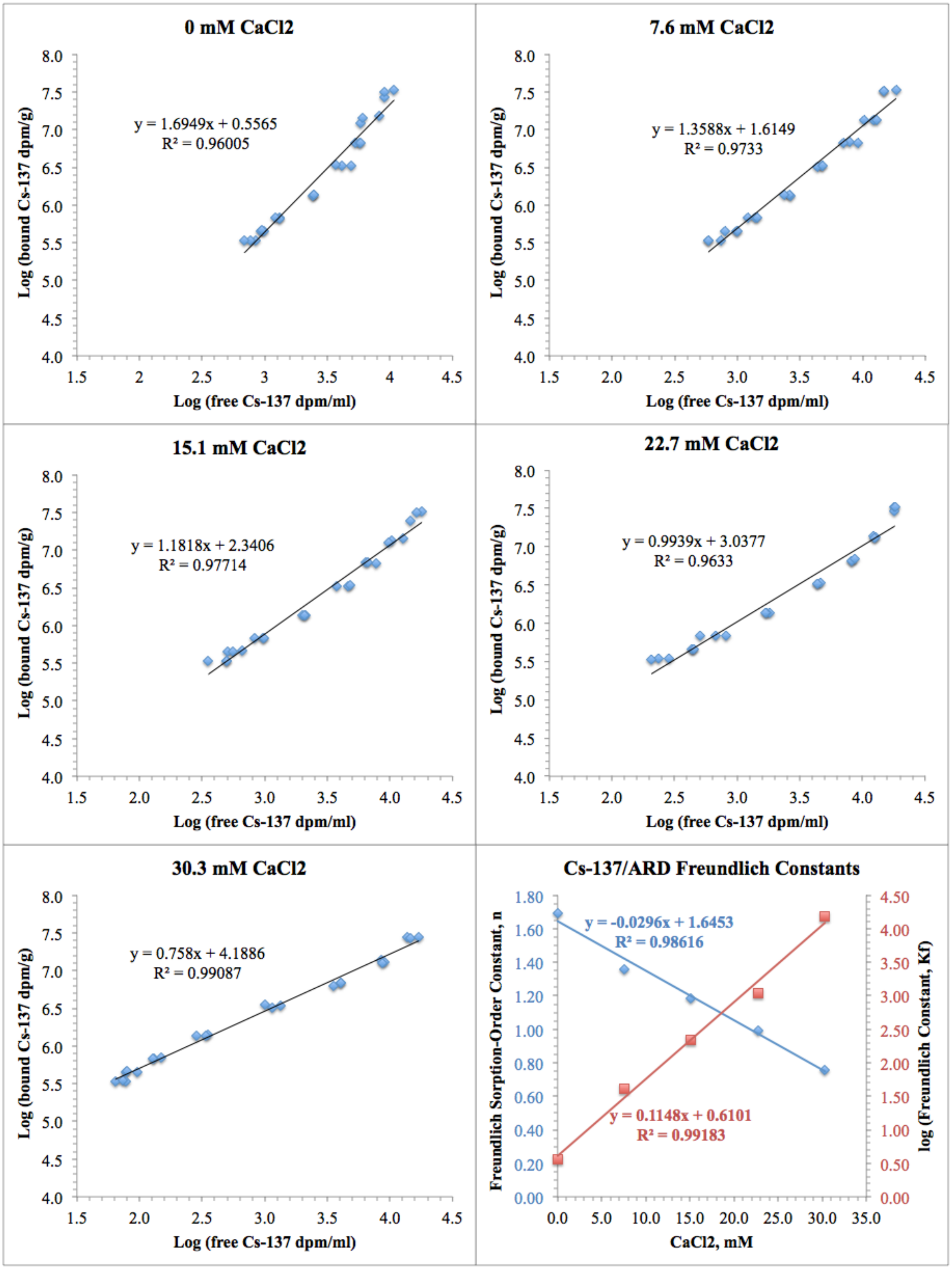

Figure 3-7. Freundlich sorption isotherms for each $CaCl_2$ concentration investigated

3.3 Wetting Agents

Dose rate reduction studies were performed using Soil$_2$O® wetting agent. Similar to the studies using fire retardant, the dose rate from stippled and dried Cs-137 solution was measured through increasing thicknesses of wetting agent. The data are shown in Figure 3-8, where it can be seen that the dose rate can be decreased by up to 17x with a thickness of 10 mm of wet Soil$_2$O® gel (greater than that achieved using the same thickness of Phos-Chek®MVP-F). It is suspected that the reduction in dose rate is due to the attenuation of beta particles through water associated with Soil$_2$O®.

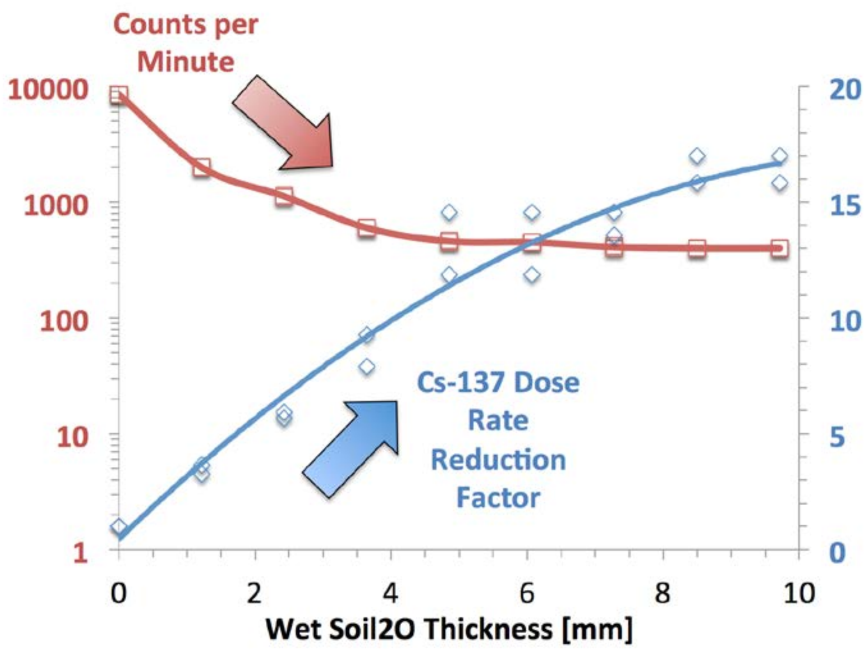

Figure 3-8. Cs-137 Measured count rate and dose rate attenuation through Soil$_2$O®wetting agent

When left to air-dry for 1.5 hours, the dose rate reduction factor for Soil$_2$O® decreased versus that for wet Soil$_2$O®, as shown in Figure 3-9. The last data point for dried material (full square) represents a sample that was air-dried over a weekend, clearly showing that with additional drying the dose rate climbed (dose rate reduction factor decreased) as water was evaporated from the Soil$_2$O® material. This supports the hypothesis that much of the dose rate reduction observed is a result of water content.

When taken to dryness, the Soil$_2$O® material cracks (as shown in Figure 3-10), and on removal from the glass dish, it was found that the Cs-137 was associated with the dried Soil$_2$O® "chips" or flakes.

As with fire retardant material, sorption studies were difficult to perform because Soil$_2$O® powder when added to water forms a gel-like material from which soluble (free) Cs-137 could not be filtered or extracted.

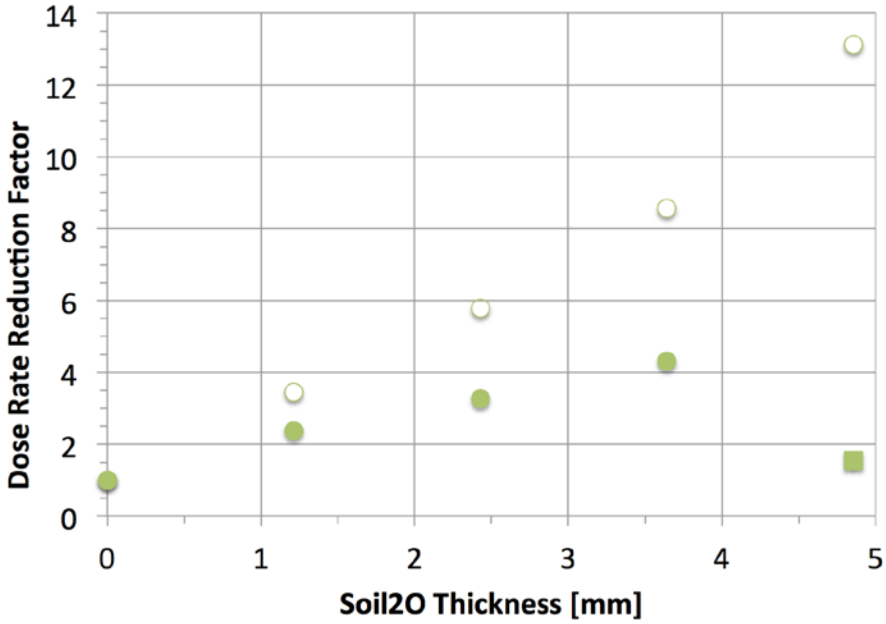

Figure 3-9. Dose rate reduction factors for wet (open circles) and dried layers (full circles) of Soil$_2$O® wetting agent

Figure 3-10. Soil$_2$O® wetting agent before and after heating / drying

4. Outdoor Demonstration of Stabilization Materials

The U.S. Environmental Protection Agency in collaboration with the Department of Homeland Security conducted the "Wide-Area Urban Radiological Contaminant, Mitigation, and Cleanup Technology Demonstration" in Columbus, Ohio on June 22-25, 2015.[13] Radiological decontamination and mitigation technologies were demonstrated on an urban building, including building and vehicle wash technologies as well as several approaches to contain wash water and radioactive particles. Demonstrations were conducted using a 75-year old brick building and the surrounding area (including parking lots) in Columbus, OH. No radioactive contaminants were applied during either demonstration, as the objective was to duplicate and implement realistic operational conditions for these technologies. As part of this demonstration, the particle containment technologies demonstrated two methods of surface disturbance, driving and walking over the 0.3 m x 0.3 m concrete pavers covered with simulated radioactive dust (same as used for vehicles above in Section 3).

The following reagents were prepared based on the manufacturers' recommendations:

- Tracer solution: 1 g PDT-6 mixed in 6 fl-oz water, 8 fl-oz isopropyl alcohol
- Phos-Chek®MVP-F (fire retardant): 100 g Phos-Chek®MVP-F added to 200 ml water to make gel/slurry
- $Soil_2O$® (dust suppression product): 5 g added to 56 fluid ounces (fl-oz) water
- $CaCl_2$ flakes: 100 g dissolved in 56 fl-oz water

According to the product website, PDT-6 tracer is an invisible green contamination simulation powder used to simulate a contaminant that can be washed off and is very luminous under long wave black light activation.[14] Pavers were sprayed twice with fluorescent PDT-6 tracer particles in solution and allowed to dry for one hour indoors (without being exposed to wind or rain). Additional pavers were left untreated to serve as blank controls and contaminant-transfer controls.

A portion of the pavers were then treated with each stabilization technology using a paint roller (in the case of Phos-Chek®MVP-F and $Soil_2O$®) or sprayed on (in the case of $CaCl_2$) and allowed to dry indoors for approximately 16 hours. Additional pavers containing tracer solution were not sprayed with stabilization to serve as positive controls. Pavers were placed indoors on a tarp-covered floor immediately before the demonstration. Pavers were spaced such that the tires contacted 5 pavers, and such that one revolution of exposed tire would contact the clean pavers.

Four vehicles (including 3 mid-size cars and one medium-sized sports utility vehicle, SUV) were used in the study. One vehicle was driven over the positive control pavers to qualitatively determine the portion of tracer particles transferred to a car tire and clean pavers without the application of stabilization material. Contamination was observed on both the tires and the transfer study pavers. This was used as the basis for comparison of pavers and tires also exposed to stabilization materials. Subsequently, cars were driven over $Soil_2O$®, $CaCl_2$ and Phos-Chek®MVP-F treated pavers. A UV light was used to highlight the presence of fluorescent tracer particles on tires and pavers. The transfer of tracer particles from the $Soil_2O$® and $CaCl_2$ treated pavers to clean pavers and tires was qualitatively less than that observed in the positive

[13] http://www.dispatch.com/content/stories/local/2015/06/25/disaster-prepared.html
[14] http://www.riskreactor.com/invisible-green-contamination-simulation-powder-detail/

control, and was approximately the same as each other. Transfer of particles from the pavers treated with Phos-Chek®MVP-F fire retardant qualitatively appeared much less than that of the control, Soil$_2$O® and $CaCl_2$. Example photographs taken during driving activities are shown in Figures 4-1, 4-2 and 4-3.

Figure 4-1. Photograph taken during driving activities over pavers coated with Phos-Chek®MVP-F fire retardant

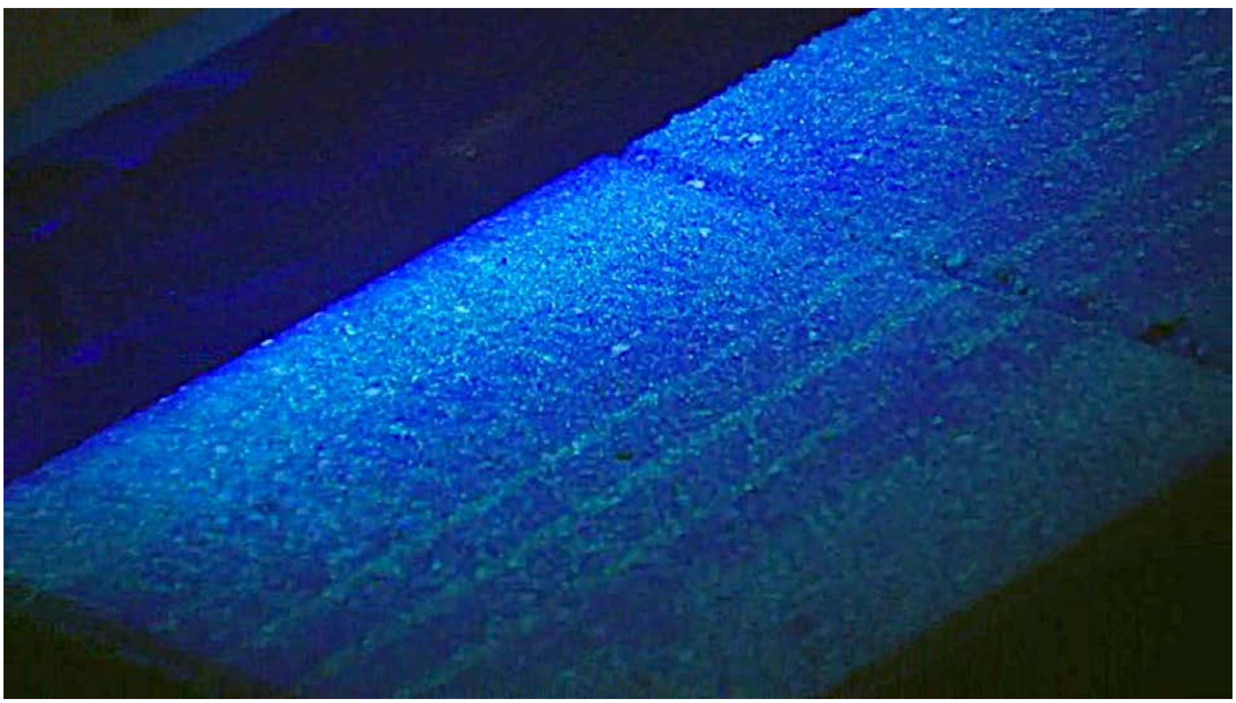

Figure 4-2. Photograph of tire tracks in particles on positive control pavers after driving

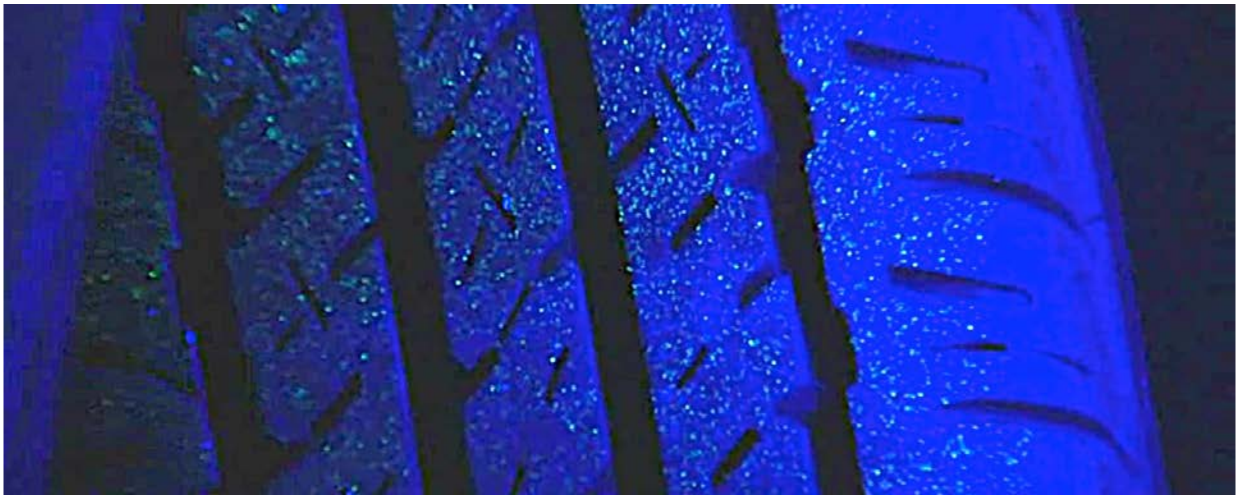

Figure 4-3. Photograph of particles transferred to tire during positive control after driving

A similar demonstration was performed using shoe covers and walking on pavers. Again, a UV light was used to highlight the presence of fluorescent tracer particles on transfer pavers and shoe covers. Pavers treated with Phos-Chek®MVP-F fire retardant were tested first by slowly walking across treated pavers and subsequently onto clean pavers. The transfer pavers and shoe covers showed very little tracer particles. Pavers treated with Soil$_2$O® and $CaCl_2$ were then evaluated again by walking across treated pavers and onto clean pavers. Transfer in these cases was greater than that observed for Phos-Chek®MVP-F. Finally, positive control pavers were walked on, showing a greater transfer of particles compared to pavers treated with stabilization technologies. Example photographs taken during the walking activities are shown in Figure 4-4. Additional information on the DHS/EPA Ohio demonstration event in 2015 can be found in *Technical Report for the Demonstration of Radiological Decontamination and Mitigation Technologies for Building Structures and Vehicles*, US EPA (2016).

Figure 4-4. Photograph taken during walking activities on fire retardant material.

5. Outdoor Testing and Semi-Quantitative Measurement of Stabilization Materials

To provide semi-quantitative data beyond the qualitative demonstration event, outdoor field-testing of each stabilization material was performed in a 40 feet (ft) by 30 ft enclosed facility located in the Northeast corner of the Lawrence Livermore National Laboratory Main site. The field test facility was enclosed within a chain link fencing with added plastic barrier material covering the lower 3 feet to protect samples from wildlife and to prevent the entry of endangered species (e.g., red legged frog) into the test facility. A 10 ft by 20 ft canopy was located within the test facility to protect samples from precipitation and to limit the amount of direct sunlight for the "sheltered" study samples (Figure 5-1).

All samples in the test facility were placed on 6 ft by 6 ft containment pallets (Figure 5-2) to collect any precipitation that may have come in contact with the stabilized samples because the laboratory has a zero materials discharged to the ground policy at the location where the test facility was located. In addition, a heavy-duty weather resistant tarp was placed on the paved surface within the test facility before any other items were placed inside. The PDT-6 fluorescent particle solution, Phos-Chek®MVP-F fire retardant, Soil$_2$O® wetting agent and $CaCl_2$ solutions were prepared as described previously in Section 4.

Figure 5-1. Field test area

Figure 5-2. Aging of pavers

The outdoor stabilization field-tests were completed using 3 in x 7 in x 2 inch (in) concrete driveway pavers purchased at a local hardware store. Pavers were purchased in bulk and used in as-received condition. Paver preparations were conducted indoors before being moved outdoors for aging and surface disturbance tests (walking and driving over pavers). Each paver was given a unique identifier. The top surface of the pavers was photographed while the fluorescent PDT-6 particles on the surface were illuminated with a light-emitting diode (LED) UV (blacklight) flashlight. The position of the paver and the distance between the light source and paver surface were held constant by using a marked photo tray and lab stand to hold items in a fixed position (Figure 5-3). A Canon Powershot A2000 IS digital camera with the flash manually disabled was used for all photographs. The exposure time (1/8 s), f-stop (f/3.2), ISO (800) and distance to sample were kept constant for all images, generating RGB-type jpg files that were 3648 x 2736 pixels.

Figure 5-3. Laboratory imaging of pavers

Images of each paver were captured at the following stages of the field study:

1) clean, as received, no particles or stabilization technology added (considered to be a blank control or background for each paver)
2) spiked with PDT-6 fluorescent particles (considered to be a positive control for each paver)
3) stabilized with each technology (i.e., Phos-Chek®MVP-F fire retardant, $Soil_2O$® dust suppression and $CaCl_2$)
4) after aging outdoors
5) after walking or driving over

For walking and driving studies, a piece of black fabric (100% cotton, 4 inch x 7.5 inch) was applied to the surface of the pavers with tape around the outside edge so as to provide a standard method of assessing transfer of particles from pavers. While fabric swatches do not have the same material properties (e.g., texture, adhesion etc.) as rubber tires and shoe soles, they provided a uniform surface that could be placed between the shoe and the tire (being subject to the same weight and movement) and were easily protected and analyzed. Treads on tires and shoe soles would greatly change the surface area contacting the particles, and analysis of that area would be difficult. It is acknowledged that the differences in material properties and surface areas of tires, shoes and fabric are a limitation of the experiment.

During walking activities, twenty steps were taken on each paver, attempting to cover as much of the paver surface as possible with each step, with the heal of the foot central to the paver and the toes emanating out towards the paver edges. During the driving study, pavers were driven over with a Chevy Silverado 2500 HD extended cab truck (curb weight approximately 5,500 lbs), with the tire contacting the paver swatch in a forward and then reverse direction to complete two total passes. Fabric swatches were then carefully removed from the paver and both paver and swatch were imaged. Similar to the pavers, each swatch was imaged before and after contacting the pavers. The studies were performed in 7 groups, shown in Table 5-1. Study 1 was abandoned due to previously selected paver incompatibility, specifically pavers in Study 1 were not within specification to allow drive-over studies, and the large size (1 ft^2) did not permit analysis indoors. Studies 2a, 2b and 3 involved walking over pavers, while studies 4 and 5 evaluated driving over pavers. Outdoor (exposed) weather conditions during the study are described in Table 5-2 utilizing LLNL's site-wide meteorological data collection, typically used to demonstrate compliance with federal, state, and local laws, regulations, and orders. DOE directives require LLNL to collect sufficient meteorological data to assess the impact of hazardous material releases on the environment and the public. On-site meteorological monitoring is required to accurately assess the transport and diffusion of airborne materials and the impacts of planned and unplanned airborne releases on public health. The meteorological data also serves as a source of conditions for outdoor testing. Aging/weathering studies were performed at time intervals of 3, 14 and 30 days.

Images of pavers and swatches taken under UV illumination were evaluated using ImageJ image analysis software (National Institutes of Health [NIH])[15]. Since pavers and swatches had some level of broad-wavelength auto-fluorescence under the UV light, digital post-processing of

[15] https://imagej.nih.gov/ij/

images was required in order to distinguish between fluorescent particles and background noise. For each image the green channel was extracted from the RGB jpg file (discarding the red and blue channels). The green channel was then background subtracted using a rolling-ball size of 50 pixels, followed by setting a threshold of 0-35/255. Finally, the image was converted to binary (white background with black particles), a region of interest (ROI) was defined, and the percentage of the ROI containing black (particles) was measured. A macro was used in ImageJ to process the large number of files (shown in Appendix B).

The region of interest was selected such that a central portion of each image would be examined; excluding any edges of pavers and fabric swatches. Settings for the macro were evaluated such that example clean paver images (blank controls) would have near-zero particles compared to spiked pavers (positive controls) that had the maximum number of particles. Results tables were converted to an Excel format in the ImageJ application and data were evaluated. Each sample had between 3 and 6 images taken at each stage. Screening of images before post-processing was performed to check image quality and sample identification (ID). Each condition (stabilization agent, walking/driving, and aging time) was performed with triplicate pavers.

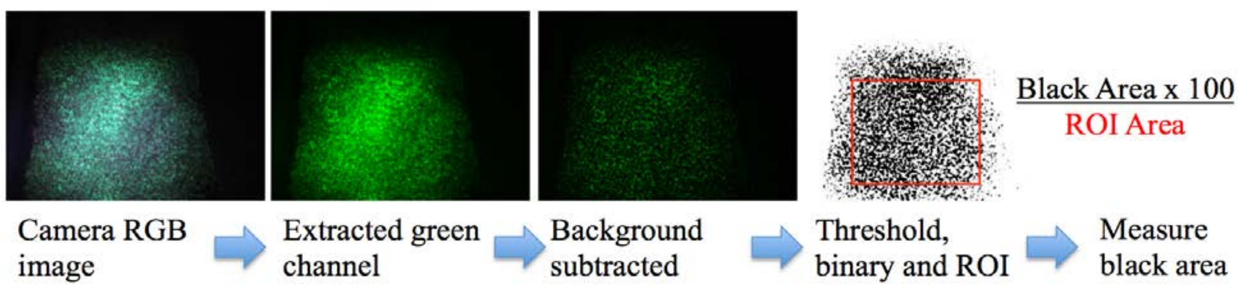

Figure 5-4. Typical images after each post-processing operation

The limitations of image analysis given the background auto-fluorescence are such that changes in surface area covered by particles (effectively how efficient are the stabilization agents in preventing transport to fabric swatches during walking and driving) can only be given in terms of factors (e.g., a factor of 2x increase in the particles on surfaces) or orders of magnitude (e.g., 10x decrease in particles on surfaces). Additional precision can only be achieved using a combination of non-auto-fluorescent materials and a physical narrow band-pass filter at the exact wavelength of the particle fluorescence between the camera and the sample. However, observations in terms of factors and orders of magnitude for this study is sufficient to determine whether the technology is viable in preventing or minimizing transport of particles from surfaces.

Post-process images were evaluated to determine the percentage of surface area within a specified region-of-interest that contained particles. Data for each aging period (3, 14 and 30 days) are grouped by the stabilization material used. The average and standard deviation for each sample are given, based on replicates of images taken for each sample. Each technology was evaluated in triplicate (3 pavers, 3 fabric swatches).

Table 5-1. Outdoor study conditions

Study Number	Test conditions	Start date	End date	Notes
1	Abandoned			Paver incompatible with study
2a - walking	No shade for 3 days	9-25-15	9-28-15	Full exposure, pavers not placed under canopy
2b - walking	No shade for 30 days	9-25-15	10-26-15	Full exposure, pavers not placed under canopy, rained on at least twice
3 - walking	Shaded for 14 days	10-13-15	10-27-15	Pavers placed underneath canopy
4 - driving	Shaded for 14 days	10-15-15	10-27-15	Pavers placed underneath canopy
5 - driving	Shaded for 27 days	10-15-15	11-11-15	Pavers placed underneath canopy. During heavy precipitation, rain was blown into canopy and most pavers were wetted

Table 5-2. Outdoor weather conditions during walking and driving studies

Date	Air Temp (deg. C)	Precipitation (in)[a]	Abs. RH g/m3	Rel. RH (%)	Dew Pt. (deg. C)	Peak Wind Gust (m/s)	Wind Speed (m/s)	Air Density kg/m3	Atm. Press. (mb)	Incoming IR (watt/m2)	Heat Flux (watt/m2)
9/25/15	14.9 - 33.6 (22.6)	0 - 0 (0)	4.58 - 9.28 (7.33)	12.3 - 61.4 (39.5)	0.8 - 10.3 (6.7)	0.2 - 8.8 (3.5)	0.2 - 5.1 (1.9)	1.13 - 1.2 (1.17)	990.1 - 992.7 (991.5)	317 - 381 (341)	-29 - 261 (59)
9/26/15	13.1 - 32.2 (22)	0 - 0 (0)	5.74 - 8.85 (7.8)	16.9 - 67.2 (42.8)	3.9 - 9.5 (7.8)	0.6 - 8.1 (3.5)	0.2 - 5.3 (2)	1.13 - 1.21 (1.17)	988.5 - 992.9 (990.8)	313 - 377 (341)	-27 - 283 (61)
9/27/15	13.7 - 30.8 (21.7)	0 - 0 (0)	5.06 - 9.21 (7.56)	16.6 - 74.4 (42.5)	2 - 10.2 (7.2)	0.4 - 5.2 (2.3)	0.2 - 2.9 (1.3)	1.13 - 1.2 (1.17)	986.8 - 989.7 (988.5)	308 - 406 (346)	-21 - 282 (40)
9/28/15	13.3 - 29.4 (19.3)	0 - 0 (0)	6.39 - 10.72 (8.95)	21.4 - 83.2 (55.2)	5.3 - 12.5 (9.6)	0.2 - 6.5 (2.9)	0.2 - 4 (1.6)	1.14 - 1.21 (1.18)	988.8 - 992.3 (990.4)	299 - 370 (340)	-10 - 356 (55)
9/29/15	13.3 - 24.1 (17.3)	0 - 0 (0)	6.36 - 10.98 (9.82)	28.2 - 89.8 (67.2)	5 - 12.6 (11)	1.5 - 6.7 (3.7)	0.8 - 3.8 (2)	1.16 - 1.21 (1.19)	991.8 - 995 (993.2)	304 - 371 (344)	-13 - 201 (45)
9/30/15	13.1 - 18.3 (15.8)	0 - 0.01 (0.02)	9.91 - 13 (11.47)	72.1 - 92.7 (82.7)	11.1 - 15.3 (13.3)	0.6 - 5.6 (2.4)	0.3 - 3.1 (1.3)	1.19 - 1.21 (1.2)	991.9 - 995.8 (993.7)	312 - 400 (367)	-14 - 83 (7)
10/1/15	14.5 - 24.4 (18.3)	0 - 0.01 (0.02)	10.27 - 12.79 (11.8)	46.5 - 92.4 (75.2)	12.1 - 15.1 (13.9)	1 - 9.2 (3.4)	0.4 - 5.6 (1.8)	1.16 - 1.21 (1.19)	992 - 996.8 (994.1)	316 - 404 (364)	-20 - 329 (41)
10/2/15	10.8 - 29 (18.7)	0 - 0 (0)	7.41 - 11.46 (9.36)	25.3 - 95.3 (62.1)	7.1 - 13.2 (10.3)	0.7 - 8.4 (2.9)	0.3 - 4.3 (1.5)	1.14 - 1.22 (1.19)	989.2 - 996.9 (993.5)	308 - 365 (338)	-28 - 309 (63)
10/3/15	9.8 - 28.4 (16.2)	0 - 0 (0)	5.46 - 9.81 (8.13)	20.2 - 85.2 (61.6)	3 - 11.3 (8.1)	0.2 - 13.5 (4.8)	0.2 - 7.8 (2.6)	1.13 - 1.22 (1.18)	976.8 - 989 (981.8)	284 - 360 (314)	-18 - 311 (69)
10/4/15	8.6 - 26 (17)	0 - 0 (0)	5.74 - 9.03 (7.68)	23.3 - 88.8 (56.5)	3.6 - 9.9 (7.3)	0.7 - 8.2 (3.3)	0.4 - 4.8 (1.8)	1.14 - 1.21 (1.18)	976.9 - 985.4 (981.4)	290 - 348 (319)	-18 - 294 (66)
10/5/15	11.1 - 25.5 (17.8)	0 - 0 (0)	7.62 - 11.27 (8.94)	31.5 - 83.3 (59.7)	7.3 - 13.2 (9.5)	0.5 - 6.8 (3.1)	0.2 - 3.7 (1.6)	1.16 - 1.21 (1.19)	985.4 - 994.9 (990)	302 - 354 (326)	-22 - 318 (61)
10/6/15	12.1 - 26.5 (18)	0 - 0 (0)	8.51 - 11.55 (10.5)	33.2 - 92.2 (69.5)	9.3 - 13.5 (12.1)	0.6 - 7.3 (3.1)	0.2 - 4.4 (1.7)	1.16 - 1.22 (1.19)	994.3 - 999.1 (997)	316 - 362 (333)	-20 - 300 (61)
10/7/15	11.9 - 29.6 (19.9)	0 - 0 (0)	8.67 - 11.53 (10.4)	28.4 - 94.6 (64)	9.8 - 13.4 (12)	0.7 - 6.6 (2.5)	0.3 - 3.4 (1.3)	1.15 - 1.22 (1.19)	996.7 - 1000 (998.5)	315 - 376 (351)	-12 - 290 (56)
10/8/15	14.2 - 31.6 (22.5)	0 - 0 (0)	7.66 - 10.33 (9.43)	23 - 80.6 (49.3)	8.1 - 12 (10.7)	0.2 - 6.8 (2.6)	0.2 - 4.4 (1.3)	1.14 - 1.21 (1.18)	995.6 - 999 (997.2)	308 - 387 (353)	-19 - 258 (47)
10/9/15	12.1 - 30.7 (21)	0 - 0 (0)	4.82 - 9.93 (7.98)	15.8 - 72.7 (46.4)	1.3 - 11.2 (8)	0.5 - 6.7 (2.8)	0.2 - 3.9 (1.5)	1.14 - 1.22 (1.18)	993.8 - 998.3 (996.2)	296 - 362 (325)	-36 - 287 (54)
10/10/15	11.7 - 27.4 (18.3)	0 - 0 (0)	7.51 - 13.14 (10.77)	39 - 92 (67.5)	6.8 - 15.9 (12.3)	0.2 - 8.8 (3.8)	0.2 - 5.1 (2.2)	1.15 - 1.22 (1.19)	993.4 - 996.5 (994.8)	298 - 356 (321)	-25 - 357 (67)
10/11/15	11.1 - 30.3 (19.8)	0 - 0 (0)	6.83 - 11.54 (9.93)	21.5 - 94.6 (62.3)	6.3 - 13.4 (11.3)	0.6 - 5.2 (2.2)	0.3 - 2.9 (1.1)	1.14 - 1.22 (1.18)	992.2 - 996.4 (994.4)	312 - 362 (341)	-22 - 274 (54)
10/12/15	11.7 - 32 (21.5)	0 - 0 (0)	7.95 - 10.07 (8.86)	23 - 85.3 (51.3)	8.6 - 11.4 (9.7)	0.2 - 8.4 (2.5)	0.2 - 4.4 (1.3)	1.13 - 1.22 (1.18)	991.7 - 995 (993.6)	304 - 367 (336)	-36 - 317 (58)
10/13/15	14.6 - 35 (23.8)	0 - 0 (0)	5.61 - 9.31 (7.77)	16.5 - 68.8 (39.8)	3.4 - 10.2 (7.8)	0.5 - 6.9 (2.6)	0.2 - 3.9 (1.4)	1.12 - 1.21 (1.17)	992.6 - 996 (994.5)	323 - 390 (353)	-25 - 268 (45)
10/14/15	15.9 - 28.6 (21)	0 - 0 (0)	4.39 - 8.7 (6.9)	17 - 59.3 (38.4)	-0.1 - 9.4 (5.7)	0.2 - 5.3 (2.2)	0.2 - 3.1 (1.2)	1.15 - 1.2 (1.18)	991.7 - 995.6 (994)	330 - 390 (361)	-82 - 205 (6)
10/15/15	16.5 - 29.1 (21.2)	0 - 0 (0)	4.89 - 11.13 (9)	25.4 - 72.2 (48.6)	1.1 - 13.1 (9.8)	0.7 - 7.5 (2.7)	0.3 - 4 (1.5)	1.14 - 1.2 (1.18)	990.8 - 993.8 (992.5)	329 - 410 (367)	-18 - 233 (33)
10/16/15	15.4 - 28.6 (19.8)	0 - 0 (0)	10.01 - 12.9 (11.39)	34.6 - 86.9 (67.2)	11.9 - 15.2 (13.4)	0.6 - 8 (2.9)	0.3 - 4.7 (1.5)	1.14 - 1.2 (1.18)	988.8 - 993.3 (991.9)	331 - 409 (370)	-36 - 315 (41)
10/17/15	15.2 - 21 (17.1)	0 - 0 (0)	10.76 - 12.08 (11.31)	62.9 - 84 (75.7)	12.4 - 14.3 (13.2)	3.8 - 7.8 (5.7)	1.6 - 4.6 (3.2)	1.18 - 1.2 (1.19)	992 - 994.9 (993.4)	309 - 399 (373)	-13 - 196 (37)
10/18/15	14.1 - 20.5 (16.8)	0 - 0 (0)	9.89 - 12.3 (11.02)	54.5 - 91 (76)	11.2 - 14.4 (12.7)	2 - 9.5 (5.9)	1 - 5.7 (3.4)	1.18 - 1.21 (1.2)	992.6 - 995.1 (994)	296 - 384 (342)	-27 - 320 (42)
10/19/15	12.4 - 22.5 (17.2)	0 - 0 (0)	9.72 - 12.17 (11.16)	47.5 - 92.3 (75.4)	11.2 - 14.2 (13)	0.5 - 8.2 (4.3)	0.4 - 4.7 (2.4)	1.17 - 1.21 (1.19)	993.2 - 996.3 (994.7)	311 - 384 (351)	-14 - 289 (56)
10/20/15	9.5 - 26.8 (17.4)	0 - 0 (0)	5.54 - 10.7 (7.88)	21.3 - 96.6 (58.7)	3.1 - 12.2 (7.5)	0.6 - 10.3 (3.4)	0.4 - 5.9 (1.8)	1.15 - 1.23 (1.19)	991.3 - 995.5 (993.4)	301 - 367 (328)	-44 - 288 (50)
10/21/15	10.4 - 26.9 (17.9)	0 - 0 (0)	5.04 - 7.64 (6.43)	19.2 - 72.1 (45.1)	1.8 - 7.1 (4.8)	0.6 - 8.1 (3.1)	0.3 - 4.7 (1.7)	1.15 - 1.22 (1.19)	991 - 994.6 (992.9)	286 - 328 (306)	-39 - 240 (45)
10/22/15	9.4 - 26.5 (17.2)	0 - 0 (0)	5.8 - 8.43 (6.93)	22.9 - 72 (49.3)	3.8 - 8.6 (5.9)	0.4 - 7.4 (2.4)	0.2 - 4.3 (1.4)	1.15 - 1.23 (1.19)	991.3 - 994.3 (992.8)	287 - 341 (311)	-16 - 286 (49)
10/23/15	9.9 - 27.8 (17.6)	0 - 0 (0)	5.39 - 8.79 (6.92)	19.6 - 77.9 (49.7)	2.8 - 9.3 (5.8)	0.5 - 4.5 (1.8)	0.3 - 2.8 (0.9)	1.15 - 1.23 (1.19)	993.3 - 995.9 (994.6)	292 - 379 (320)	-34 - 198 (37)
10/24/15	9.3 - 26.9 (17.6)	0 - 0 (0)	6.04 - 8.82 (7.38)	26.4 - 75.9 (51.1)	4.2 - 9.5 (6.8)	0.5 - 5.9 (2)	0.3 - 3.1 (1.1)	1.15 - 1.23 (1.19)	992 - 995.8 (994)	287 - 362 (327)	-9 - 197 (33)
10/25/15	10.6 - 24.4 (17)	0 - 0 (0)	7.33 - 11.84 (9.14)	33.1 - 89.1 (63)	6.8 - 14.1 (9.9)	0.7 - 7.5 (3.3)	0.3 - 3.8 (1.8)	1.16 - 1.22 (1.19)	992.5 - 995.8 (994)	287 - 355 (322)	-15 - 236 (44)
10/26/15	7 - 25.5 (16)	0 - 0 (0)	6.62 - 10.28 (8.56)	28.1 - 98.6 (66.2)	5.6 - 11.5 (8.9)	0.5 - 6.5 (2.1)	0.2 - 3.4 (1.1)	1.16 - 1.24 (1.2)	992.2 - 995.7 (994)	288 - 365 (327)	-15 - 240 (44)
10/27/15	12.9 - 20.8 (17)	0 - 0 (0)	7.84 - 10.95 (9.23)	49.4 - 79.6 (62.5)	7.5 - 12.6 (10.1)	0.7 - 8.7 (2.3)	0.3 - 4.4 (1.2)	1.18 - 1.21 (1.2)	992.8 - 996.3 (994.6)	323 - 379 (361)	-12 - 109 (11)
10/28/15	10.7 - 21.9 (16.2)	0 - 0.01 (0.01)	9.1 - 11.83 (10.72)	50.7 - 95.7 (77.3)	10.1 - 13.8 (12.3)	0.5 - 7.8 (3.2)	0.3 - 4.4 (1.7)	1.17 - 1.22 (1.2)	993.9 - 996.8 (995.4)	306 - 398 (340)	-17 - 278 (33)
10/29/15	8.1 - 25 (15.3)	0 - 0 (0)	4.51 - 10.83 (7.44)	19.1 - 98.2 (63.1)	0.2 - 12.3 (6.4)	0.5 - 11 (3)	0.3 - 6.1 (1.6)	1.16 - 1.23 (1.2)	992.7 - 996.2 (994.5)	281 - 365 (317)	-29 - 248 (43)
10/30/15	8.1 - 28.3 (17.1)	0 - 0 (0)	3.97 - 7.11 (5.98)	13.9 - 73.4 (45.5)	-1.4 - 6.3 (3.6)	0.7 - 4.9 (2.2)	0.3 - 2.6 (1.1)	1.15 - 1.23 (1.2)	993.7 - 996.8 (995.3)	280 - 341 (309)	-18 - 223 (38)
10/31/15	9.8 - 29.8 (18.6)	0 - 0 (0)	6.11 - 12.07 (7.8)	21.4 - 92 (51.5)	4.1 - 14.1 (7.4)	0.3 - 7.4 (3)	0.2 - 3.6 (1.7)	1.15 - 1.23 (1.19)	995.8 - 999.4 (997.3)	299 - 384 (327)	-32 - 272 (36)
11/1/15	12.1 - 23.5 (17.6)	0 - 0 (0)	10.37 - 13.45 (11.57)	49.8 - 94.5 (76.1)	11.6 - 15.9 (13.5)	1.4 - 7.5 (4.3)	0.9 - 4 (2.4)	1.17 - 1.22 (1.2)	992.7 - 1000.5 (997.4)	303 - 394 (355)	-9 - 211 (44)
11/2/15	9.3 - 17.1 (12.6)	0 - 0.11 (1.4)	7.64 - 13.85 (9.99)	64.4 - 95.3 (87.6)	7.1 - 16.3 (11)	0.7 - 10.6 (3.8)	0.4 - 4.7 (1.9)	1.19 - 1.22 (1.21)	986.2 - 992.6 (989)	342 - 396 (369)	-59 - 76 (4)
11/3/15	6.5 - 16.9 (11.2)	0 - 0.01 (0.01)	4.74 - 8.96 (7.09)	32.8 - 98.8 (72.1)	0.5 - 9.3 (5.7)	0.5 - 9.2 (3.1)	0.3 - 5.7 (1.7)	1.19 - 1.24 (1.22)	988.2 - 993.4 (991.4)	268 - 368 (307)	-23 - 178 (30)
11/4/15	4.6 - 16.4 (10)	0 - 0 (0)	3.31 - 7.33 (4.98)	23.2 - 96.5 (56.5)	-4.4 - 6.2 (0.5)	0.8 - 11.6 (4.4)	0.4 - 7.3 (2.4)	1.2 - 1.25 (1.23)	993.1 - 999.8 (996)	246 - 313 (270)	-62 - 200 (34)
11/5/15	2.8 - 17.7 (9.4)	0 - 0 (0)	3.94 - 6.18 (5.24)	28 - 90.4 (61.3)	-2.1 - 3.8 (1.4)	0.4 - 6 (1.9)	0.3 - 2.7 (1)	1.2 - 1.27 (1.24)	999.6 - 1004.3 (1002.4)	252 - 319 (276)	-25 - 231 (35)
11/6/15	3.8 - 18.9 (10.4)	0 - 0 (0)	4.34 - 6.71 (5.58)	26.9 - 93 (62.2)	-0.8 - 5.1 (2.4)	0.5 - 6.2 (2)	0.3 - 3.9 (1)	1.2 - 1.26 (1.23)	1001.5 - 1005 (1003.2)	260 - 314 (281)	-6 - 200 (39)
11/7/15	3.6 - 18 (10)	0 - 0 (0)	5.77 - 7.13 (6.46)	37.2 - 94.7 (70.7)	3 - 6 (4.5)	0.5 - 6 (2)	0.3 - 3.9 (1.2)	1.19 - 1.26 (1.23)	995.6 - 1001.7 (998.7)	265 - 322 (287)	-5 - 241 (39)
11/8/15	4.2 - 14.7 (10.2)	0 - 0.02 (0.03)	6.3 - 10.74 (8.15)	64.4 - 96.5 (83.4)	3.9 - 12.2 (7.7)	0.5 - 6.7 (3)	0.3 - 4.1 (1.7)	1.2 - 1.25 (1.22)	992.6 - 996.5 (994.6)	273 - 384 (328)	-27 - 77 (7)
11/9/15	6.1 - 12.3 (9.3)	0 - 0.11 (0.45)	6.92 - 8.68 (7.74)	70 - 96.4 (84.4)	5.4 - 8.8 (7.1)	0.5 - 9.7 (4.2)	0.3 - 5 (2.3)	1.21 - 1.24 (1.23)	991.7 - 995.9 (993.3)	264 - 365 (308)	-58 - 91 (-2)
11/10/15	3.7 - 13.3 (8.8)	0 - 0 (0)	6.31 - 7.59 (7.1)	55.3 - 97.9 (80)	3.7 - 6.8 (5.8)	0.5 - 8.5 (2.6)	0.3 - 4.1 (1.5)	1.22 - 1.27 (1.24)	996 - 1006.7 (1001.7)	261 - 344 (309)	-17 - 155 (21)
11/11/15	1.9 - 15.1 (7.8)	0 - 0.01 (0.01)	5.66 - 7.58 (6.53)	46.2 - 99.9 (80.7)	1.9 - 6.9 (4.4)	0.5 - 5.2 (1.9)	0.3 - 3.3 (1)	1.22 - 1.28 (1.25)	1005.3 - 1008.8 (1006.9)	263 - 334 (290)	-26 - 219 (30)
11/12/15	1.9 - 15.8 (8.3)	0 - 0 (0)	5.27 - 7.18 (6.19)	41.7 - 98.3 (74.8)	1.8 - 6.1 (3.8)	0.2 - 5.6 (2)	0.2 - 3.6 (1.1)	1.21 - 1.27 (1.24)	998.9 - 1005.4 (1002.2)	264 - 331 (290)	-17 - 177 (30)
11/13/15	3 - 16.4 (9)	0 - 0 (0)	5.97 - 7.62 (6.79)	46.9 - 98.3 (77.8)	3 - 6.9 (5.1)	0.5 - 7.1 (2.4)	0.2 - 4.8 (1.4)	1.2 - 1.26 (1.23)	995 - 999.2 (997.2)	271 - 333 (296)	-23 - 187 (28)
11/14/15	2.5 - 19.8 (10.4)	0 - 0 (0)	5.88 - 8.75 (7.11)	34.1 - 99.5 (75.2)	2.5 - 9.1 (5.8)	0.5 - 8.5 (2.7)	0.3 - 5.3 (1.5)	1.18 - 1.26 (1.22)	989.5 - 995.4 (992.1)	275 - 350 (299)	-51 - 143 (18)
11/15/15	7.3 - 14.4 (10.8)	0 - 0.05 (0.29)	5.04 - 9.48 (7.08)	50.1 - 94.2 (69.9)	1.1 - 10.2 (5.6)	1.4 - 12.2 (6.9)	0.8 - 6.6 (3.5)	1.2 - 1.24 (1.22)	986.1 - 997 (990.7)	250 - 364 (304)	-84 - 204 (10)
11/16/15	3.4 - 14.3 (8.5)	0 - 0 (0)	2.06 - 5.13 (3.7)	16.3 - 73.3 (45.7)	-10.6 - 1.1 (-3.7)	0.7 - 13 (5.7)	0.3 - 7.4 (3.2)	1.22 - 1.27 (1.24)	996.7 - 1005.8 (1002.7)	237 - 261 (251)	-41 - 146 (20)

Note: values are daily min – max (average), except [a]precipitation: min – max (sum). All values are at ground level for LLNL site (which includes, but not specific to, the test location). Data courtesy of LLNL's site-wide meteorological data collection.

5.1 Walking Disturbance Studies

The results of the walking study after 3 days of aging outdoors are tabulated in Table 5-3. These samples were exposed to direct sunlight and temperatures ranging from 13.1 to 33.6°C (55 to 92°F), no rain, average wind gusts of 3 m/s, and an average heat flux of 54 Watts per square meter (W/m^2) based on LLNL site meteorological data. The control sample (no stabilization material) showed no significant change after being outdoors for 3 days. Two of the three samples showed greater than 2x loss of particles from pavers during walking, and transfer onto fabric swatches showed a variety of results, from no transfer to greater than two orders of magnitude transfer. It is important to note here that this study was one of the first undertaken, so experimental variability was higher than for other studies.

Table 5-3. Percentage area particle coverage, 3-day aging study 2a with walking disturbance

Control	Clean		Spike		Stab		Aged		Walked		Clean Felt		Walked Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S2-P1	0.35	0.10	34.77	3.00	-	-	36.39	3.98	24.35	1.25	1.55	0.42	1.39	0.51
S2-P2	1.43	1.48	26.06	1.00	-	-	14.55	1.95	6.98	0.64	0.01	0.00	0.85	1.75
S2-P3	0.30	0.00	20.40	0.37	-	-	13.69	1.18	5.01	1.85	0.01	0.00	0.01	0.01

Soil2O	Clean		Spike		Stab		Aged		Walked		Clean Felt		Walked Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S2-P7	0.26	0.02	35.51	1.19	15.45	0.95	19.82	0.46	12.96	1.03	0.00	0.00	0.00	0.00
S2-P8	0.21	0.02	33.71	6.76	21.61	0.94	13.78	0.71	7.20	2.11	-	-	0.06	0.04
S2-P9	0.18	0.02	37.57	1.62	17.77	1.11	29.43	1.60	27.48	1.40	0.55	0.01	0.56	0.02

CaCl2	Clean		Spike		Stab		Aged		Walked		Clean Felt		Walked Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S2-P16	-	-	21.55	1.03	14.86	1.68	26.81	8.04	20.01	3.51	0.02	0.01	0.01	0.00
S2-P17	0.05	0.00	13.14	1.94	9.08	1.24	14.08	0.90	50.94	1.23	0.07	0.03	1.53	0.84
S2-P18	0.03	0.00	12.32	1.62	10.48	1.22	38.53	2.56	31.37	2.02	0.35	0.04	0.47	0.03

MVP	Clean		Spike		Stab		Aged		Walked		Clean Felt		Walked Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S2-P19	0.02	0.00	20.23	0.00	1.42	0.48	2.73	0.73	2.37	1.27	0.05	0.00	0.10	0.00
S2-P20	0.03	0.00	22.67	3.69	0.79	0.51	1.08	0.26	1.26	0.04	0.34	0.11	1.28	0.08
S2-P24	-	-	26.29	6.23	1.04	0.22	1.69	0.07	1.19	0.28	0.06	0.01	0.17	0.01

Notes: Dashes indicate individual samples not analyzed. Clean = blank control. Spike = only PDT-6 added. Stab = PDT-6 plus stabilizer. Aged = PDT-6 plus stabilizer and aged for the number of study days. Walked = paver after walking. Clean felt = transfer material blank control. Walked Felt = transfer measurement after walking.

The corresponding experiments incorporating $Soil_2O^{®}$, $CaCl_2$ and Phos-Chek®MVP-F fire retardant showed promising results. In the case of $Soil_2O^{®}$ dust wetting agent, there was less than a factor of 2x loss of particles from pavers during walking, and negligible transfer onto fabric swatches. Following $CaCl_2$ application, loss of particles from pavers was approximately the same as that for $Soil_2O^{®}$, although one sample did show a 20x increase in particles on a fabric swatch after walking on treated pavers. The application of Phos-Chek®MVP-F fire retardant on pavers reduced the number of particles visible before walking, due to the opaque nature of the Phos-Chek®MVP-F material (which differs from the other two products tested). Loss of particles during 3 day aging was similar to that observed for $CaCl_2$ and transfer of particles onto fabric swatches increased by factors of 2x to 4x. During the 3-day outdoor aging study, it appears that all three technologies reduced the transfer of particles, with $Soil_2O^{®}$ and Phos-Chek®MVP-F fire retardant performing similarly, and $CaCl_2$ yielding higher transfer.

The results of the walking disturbance study after 14 days of aging outdoors are tabulated in Table 5-4. These samples were stored outside under shade and exposed to temperatures ranging from 7 to 35°C (45 to 95°F), no rain, average wind gusts of 3 m/s, and an average heat flux of 38 W/m^2. The control pavers showed no significant loss of particles during the 14-day aging, no significant measurable loss of particles from pavers during walking, but two of the three control fabric swatches did show almost an order of magnitude difference in particles between clean and exposed.

Table 5-4. Percentage area particle coverage, 14-day aging study 3 with walking disturbance

Control	Clean		Spike		Stab		Aged		Walked		Clean Felt		Walked Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S3-P1	0.00	0.00	50.01	0.18	-	-	34.47	8.36	33.56	4.11	0.01	0.00	0.12	0.01
S3-P2	-	-	33.50	1.47	-	-	19.11	2.15	15.15	2.49	0.01	0.00	0.01	0.00
S3-P3	-	-	29.17	8.16	-	-	33.06	7.30	34.63	1.69	0.01	0.00	0.11	0.12

Soil2O	Clean		Spike		Stab		Aged		Walked		Clean Felt		Walked Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S3-P7	-	-	25.03	0.82	31.89	1.77	10.35	4.51	18.51	0.77	0.00	0.00	0.02	0.00
S3-P8	-	-	22.05	0.70	22.26	2.29	16.53	2.04	16.32	0.76	0.00	0.00	0.00	0.00
S3-P9	-	-	18.35	2.53	21.71	1.73	31.66	2.18	-	-	0.03	0.04	0.01	0.01

CaCl2	Clean		Spike		Stab		Aged		Walked		Clean Felt		Walked Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S3-P10	-	-	27.81	0.13	11.19	0.99	25.28	1.74	24.61	0.91	0.01	0.00	0.04	0.01
S3-P11	-	-	30.77	1.92	32.38	0.12	3.59	1.08	3.36	1.52	0.00	0.00	0.00	0.00
S3-P12	-	-	16.20	1.42	6.52	1.94	3.00	0.78	1.47	0.16	-	-	0.00	0.00

MVP	Clean		Spike		Stab		Aged		Walked		Clean Felt		Walked Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S3-P4	-	-	25.30	1.35	1.19	0.19	3.03	1.21	1.91	1.04	0.08	0.04	0.01	0.00
S3-P5	-	-	28.02	0.73	1.40	0.04	2.19	0.38	2.21	0.72	0.07	0.00	0.06	0.00
S3-P6	-	-	16.12	0.58	0.39	0.02	0.60	0.11	1.22	0.26	0.00	0.00	0.00	0.00

Notes: Dashes indicate individual samples not analyzed. Clean = blank control. Spike = only PDT-6 added. Stab = PDT-6 plus stabilizer. Aged = PDT-6 plus stabilizer and aged for the number of study days. Walked = paver after walking. Clean felt = transfer material blank control. Walked Felt = transfer measurement after walking.

The corresponding pavers covered with Soil$_2$O®, $CaCl_2$ and Phos-Chek®MVP-F fire retardant showed changes on aging. Pavers coated with Soil$_2$O® and $CaCl_2$ in some cases showed a loss of particles, whereas Phos-Chek®MVP-F showed a gain in particles compared to the stabilized images. This is not surprising given that Phos-Chek®MVP-F masks the particles, and suggests that some Phos-Chek®MVP-F was lost from the surface without losing particles, whereas particles were likely lost with Soil$_2$O® (showing approximately a 5x increase in particles on a fabric swatch) and $CaCl_2$ (similar to the control with no stabilization technology). None of the technologies resulted in a measureable loss of particles from the surface of the pavers, but there was some transfer onto fabric swatches in the case of Soil$_2$O® and $CaCl_2$. There was no significant transfer of particles onto fabric swatches in the case of Phos-Chek®MVP-F. The 14-day outdoor aging study results suggest that Phos-Chek®MVP-F fire retardant provides the best longer term efficacy for preventing transfer of particles, despite some loss of the material over the 14 days.

Samples exposed for 30 days saw quite different environmental conditions compared to the shorter timescale studies detailed above. Pavers were not sheltered under a canopy and subsequently experienced rain events on two days early in the study, with up to 0.02 inch (0.5

mm) of precipitation. Pavers were exposed to temperatures ranging from 7 to 35°C (45 to 95°F). Average wind gusts were 3 m/s with a maximum of 13.5 m/s and an average heat flux of 48 W/m^2. The control samples showed a varying degree of particles lost from the surface during aging/rain, ranging from almost a 4x to over 200x decrease. For pavers covered with $Soil_2O^®$, aging for 30 days showed varying factors of loss, from approximately 3x to 17x and therefore some particles did remain on the surface even after the unexpected rain exposure. With the exception of one paver for which an increase in particles after walking was observed and a measurable transfer of particles to the fabric swatch, walking did not result in a significant change in the particle loading on pavers covered with $Soil_2O^®$. For $CaCl_2$ and Phos-Chek®MVP-F fire retardant, results were similar to $Soil_2O^®$; specifically, a significant reduction in particles occurred after aging and resulting in no appreciable transfer to fabric swatches on walking. The results for the 30-day study show that none of the stabilization technologies can reliably contain particulates after rain/wind events, which was surprising.

Table 5-5. Percentage area particle coverage, 30-day aging study 2b with walking disturbance

Control	Clean		Spike		Stab		Aged		Walked		Clean Felt		Walked Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S2-P4	-	-	15.02	0.45	-	-	0.47	0.04	0.41	0.06	0.01	0.00	0.00	0.00
S2-P5	-	-	27.01	1.68	-	-	0.12	0.08	0.40	0.25	0.05	0.01	0.00	0.00
S2-P6	-	-	24.00	0.78	-	-	6.30	2.97	5.28	0.83	0.12	0.04	0.10	0.05

Soil2O	Clean		Spike		Stab		Aged		Walked		Clean Felt		Walked Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S2-P13	0.10	0.02	9.83	1.90	15.98	1.48	5.85	1.95	5.19	2.25	0.00	0.00	0.00	0.00
S2-P14	0.22	0.05	36.44	3.29	17.91	0.39	1.04	0.46	15.41	2.44	0.00	0.00	0.19	0.12
S2-P15	0.05	0.00	20.84	2.69	18.59	4.96	2.15	1.05	1.36	0.89	0.04	0.01	-	-

CaCl2	Clean		Spike		Stab		Aged		Walked		Clean Felt		Walked Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S2-P10	0.24	0.02	27.14	2.64	7.79	2.37	0.08	0.04	0.20	0.15	0.00	0.00	0.00	0.00
S2-P11	0.09	0.01	14.74	0.97	10.16	2.30	1.07	0.33	0.72	0.31	0.01	0.00	0.01	0.00
S2-P12	0.73	0.08	25.79	3.87	14.86	1.90	8.76	0.78	6.17	0.65	0.02	0.01	0.01	0.00

MVP	Clean		Spike		Stab		Aged		Walked		Clean Felt		Walked Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S2-P21	-	-	24.43	2.45	0.85	0.02	1.10	0.24	1.67	0.03	0.00	0.00	0.00	0.00
S2-P22	-	-	35.88	2.24	2.69	0.12	1.58	0.46	3.27	1.40	0.00	0.00	0.00	0.00
S2-P23	-	-	21.59	4.78	0.70	0.15	1.21	0.52	1.02	0.42	0.01	0.00	0.01	0.00

Notes: Dashes indicate individual samples not analyzed. Clean = blank control. Spike = only PDT-6 added. Stab = PDT-6 plus stabilizer. Aged = PDT-6 plus stabilizer and aged for the number of study days. Walked = paver after walking. Clean felt = transfer material blank control. Walked Felt = transfer measurement after walking.

5.2 Driving Disturbance Studies

During the 14-day aging study followed by driving disturbance, pavers were stored under a canopy and were exposed to temperatures ranging from 7 to 29°C (45 to 84°F), no precipitation, average wind gusts of 3 m/s with a maximum of 10 m/s, and an average heat flux of 56 W/m^2. The results are shown in Table 5-6. The positive control sample showed very little loss on aging under the weathering conditions. Driving over the positive control resulted in up to 4x loss of material and deposition of particles on the swatch. Results for $Soil_2O^®$ and $CaCl_2$ stabilization technologies after aging under the same conditions followed by driving were similar in that negligible loss of particles was observed during aging, but significant transfer of particles onto swatches after driving disturbance was observed. For Phos-Chek®MVP-F fire retardant, negligible particle transfer onto fabric swatches occurred when pavers were driven over after 14 days of outdoor aging.

Table 5-6. Percentage area particle coverage, 14-day aging study 4 with driving disturbance

Control	Clean		Spike		Stab		Aged		Driven		Clean Felt		Driven Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S4-P1	0.00	0.00	55.61	2.66	-	-	32.79	0.92	29.85	1.88	0.01	0.00	0.13	0.08
S4-P2	-	-	33.50	1.47	-	-	39.50	2.72	16.33	0.88	0.04	0.00	0.03	0.00
S4-P3	-	-	29.17	8.16	-	-	29.00	3.15	7.62	3.40	0.02	0.01	0.10	0.05

Soil2O	Clean		Spike		Stab		Aged		Driven		Clean Felt		Driven Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S4-P7	-	-	25.03	0.82	-	-	31.02	3.36	38.68	1.37	0.17	0.01	0.04	0.00
S4-P8	-	-	22.05	0.70	22.26	2.29	20.51	3.68	20.86	2.57	0.01	0.00	0.15	0.03
S4-P9	-	-	18.35	2.53	21.71	1.73	30.40	3.26	34.12	3.87	0.01	0.00	0.11	0.01

CaCl2	Clean		Spike		Stab		Aged		Driven		Clean Felt		Driven Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S4-P10	-	-	34.58	2.23	29.02	1.57	39.95	1.60	35.77	1.13	0.01	0.00	0.11	0.05
S4-P11	-	-	39.93	0.33	22.46	1.51	25.18	2.09	12.86	1.27	0.01	0.00	0.56	0.20
S4-P12	-	-	40.29	1.49	22.65	2.13	18.76	2.91	32.75	1.81	0.00	0.00	0.35	0.14

MVP	Clean		Spike		Stab		Aged		Driven		Clean Felt		Driven Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S4-P4	-	-	25.30	1.35	-	-	1.01	0.23	1.78	0.73	0.13	0.03	0.02	0.02
S4-P5	-	-	28.02	0.73	-	-	0.87	0.24	1.11	0.03	0.18	0.01	0.03	0.02
S4-P6	-	-	16.12	0.58	-	-	1.29	0.36	-	-	0.01	0.00	0.00	0.00

Notes: Dashes indicate individual samples not analyzed. Clean = blank control. Spike = only PDT-6 added. Stab = PDT-6 plus stabilizer. Aged = PDT-6 plus stabilizer and aged for the number of study days. Driven = paver after driving. Clean felt = transfer material blank control. Driven Felt = transfer measurement after driving.

During the 27-day aging study, pavers were stored under a canopy and were exposed to temperatures ranging from 1.9 to 29.8°C (35 to 86°F), average wind gusts of 3 m/s with a maximum of 12 m/s and an average heat flux of 34 W/m^2. Rain events occurred on 6 of the 27 days, but because pavers were under a canopy, most precipitation was not a problem. On two days, significant precipitation occurred together with strong gusts (1.4 inch total rain with 11 m/s gusts on 11/2/15 and 0.45 inch total rain with 10 m/s gusts on 11/9/15). During these two weather events, rain blew under the canopy and pavers were wetted.

Table 5-7. Percentage area particle coverage, 27-day aging study 5 with driving disturbance

Control	Clean		Spike		Stab		Aged		Driven		Clean Felt		Driven Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S5-P1	-	-	34.34	1.16	-	-	10.52	3.05	7.69	1.15	0.00	0.00	0.01	0.00
S5-P2	-	-	40.14	0.22	-	-	13.24	2.15	7.73	2.09	0.04	0.00	0.02	0.01
S5-P3	-	-	40.33	1.35	-	-	10.15	1.21	7.90	0.44	0.00	0.00	0.00	0.00

Soil2O	Clean		Spike		Stab		Aged		Driven		Clean Felt		Driven Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S5-P7	-	-	25.57	9.90	-	-	15.61	1.14	40.27	1.66	0.03	0.01	0.15	0.06
S5-P8	-	-	25.37	4.71	-	-	17.53	1.87	16.79	1.36	0.00	0.00	0.07	0.00
S5-P9	-	-	25.79	8.31	33.22	0.69	9.91	0.47	13.17	0.77	0.00	0.00	0.02	0.00

CaCl2	Clean		Spike		Stab		Aged		Driven		Clean Felt		Driven Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S5-P10	-	-	25.83	3.24	20.82	3.38	6.18	1.33	1.28	0.38	0.02	0.02	0.00	0.00
S5-P11	-	-	31.93	6.46	-	-	3.38	0.78	6.43	0.88	0.00	0.00	0.02	0.00
S5-P12	-	-	35.12	1.55	-	-	9.48	0.55	6.65	1.50	0.07	0.00	0.01	0.00

MVP	Clean		Spike		Stab		Aged		Driven		Clean Felt		Driven Felt	
Paver	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
S5-P4	-	-	43.88	0.65	0.78	0.04	2.70	1.32	7.86	0.38	0.07	0.00	0.12	0.00
S5-P5	-	-	33.02	12.10	0.91	0.14	1.62	0.54	2.45	0.17	0.01	0.00	0.32	0.04
S5-P6	-	-	40.14	3.52	0.52	0.08	-	-	2.29	0.64	0.01	0.00	0.01	0.00

Note: Dashes indicate individual samples not analyzed

The results of the driving disturbance study on pavers aged outdoors for 27 days are tabulated in Table 5-7. The positive control pavers show a 3x decrease in particles on aging for 27 days, which was more than the 14-day study. This result was potentially due to the rain events that subsequently showed negligible particle transfer from the paver to the swatch during driving activities. Results for pavers treated with Soil$_2$O® and $CaCl_2$ stabilization technologies showed similar loss of particles during aging, however there was significant transfer of particles on some pavers in both cases. Pavers treated with Phos-Chek®MVP-F fire retardant showed a 2x to 3x increase in visible particles on aging. Because Phos-Chek®MVP-F is opaque, this increase may be due to removal of Phos-Chek®MVP-F from the surface, leaving more particles visible compared to initially stabilized images. Subsequent driving over pavers coated with Phos-Chek®MVP-F fire retardant show negligible transfer to swatches placed between the paver and the tire.

The results of both the 14-day and 27-day aging studies followed by driving show more transfer of particles from pavers for Soil$_2$O® and $CaCl_2$ than for Phos-Chek®MVP-F fire retardant despite the two studies experiencing different weathering conditions.

5.3 Discussion of Outdoor Test Results

The relative efficacy of each technology in preventing removal of particles during walking and driving disturbance activities can be determined for each technology. The results are shown graphically in Figure 5-5 and 5-6, with median transfer factors onto fabric swatches. The transfer factor is determined by dividing the percentage area of the image ROI containing particles for a fabric swatch following walking or driving, by the percentage area of the image ROI for the corresponding clean swatch before walking or driving.

Transfer of particles from control pavers was similar during both walking and driving activities, with a median transfer factor of 3x for walking after 3 days of aging, between 6x and 8x for driving and walking after 14 days of aging, and 1x for both driving and walking after 27 and 30 days of aging respectively. The latter 27- and 30-day results may have been catastrophically impacted by rain events. No driving experiments were performed following 3 days of aging.

For stabilization technologies, transfer factors were typically lower when walking over pavers after 3 and 14 days of aging, with Soil$_2$O® and $CaCl_2$ performing slightly better than Phos-Chek®MVP-F fire retardant. Results of walking on pavers after 30 days of aging showed a very high transfer factor for Soil$_2$O®, less for $CaCl_2$ and Phos-Chek®MVP-F, but were likely impacted by rain events.

Transfer of particles during driving over pavers treated with stabilization technologies showed a median transfer factor for Soil$_2$O® of 10x. By comparison, the median transfer factor for $CaCl_2$ was 91x and approximately 1x for Phos-Chek®MVP-F (~1x). Median transfer factors during driving over pavers aged for 27 days were 6x for Soil$_2$O®, 3x for $CaCl_2$ and 2x for Phos-Chek®MVP-F, although these latter results may have been impacted by rain events.

The results show that the application of stabilization technologies on surfaces can reduce the transfer of particles removed from pavers during walking and driving. The performance of these materials appears dependent on the presence of precipitation and subsequent run-off from surfaces.

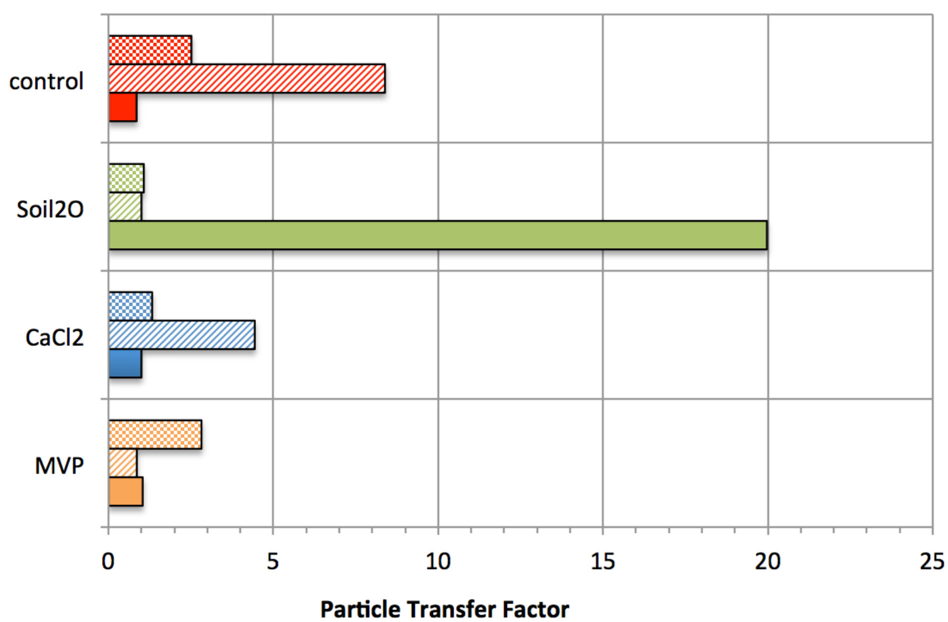

Figure 5-5. Median particle transfer factor for aged stabilization technologies under walking disturbance

Legend: Control (red), Soil$_2$O® (green), $CaCl_2$ (blue), Phos-Chek®MVP-F (orange). Aging: 3 day (checkered), 14 day (diagonal stripes), 30 day walking and 27 day driving (solid)

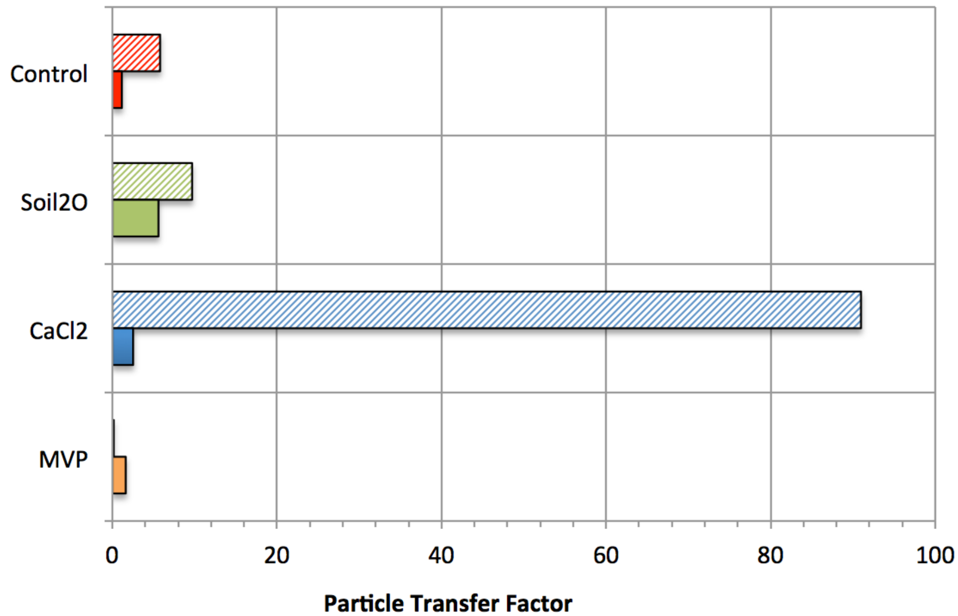

Figure 5-6. Median particle transfer factors for aged stabilization technologies under driving disturbance

<u>Legend</u>: Control (red), $Soil_2O^{®}$ (green), $CaCl_2$ (blue), Phos-Chek®MVP-F (orange). Aging: 3 day (checkered), 14 day (diagonal stripes), 30 day walking and 27 day driving (solid)

6. Quality Assurance (QA)

6.1 Literature Survey of Stabilization Materials

The evaluation of literature and information pertaining to stabilization materials is described in Section 2 of this report. The work was performed according to a Quality Assurance Project Plan (QAPP) for the identification of technical gaps in radiological contamination containment technologies (Sutton, 2014a).

Four sources of information were used to understand technical gaps, and they are ranked in order of reliability:

1. Peer-reviewed journal articles and conference abstracts
2. Government reports
3. Commercial vendor reports
4. Commercial and community websites

By nature of their review by peers, journal articles and some conference abstracts are considered trusted sources of information. Similarly, reports published by government agencies such as US EPA, US DOE, Interstate Technology Regulatory Council (ITRC) were considered highly trust-worthy. Additionally, government sources may include State and Local documents and websites. International governmental reports were also utilized, including those from the UK and EU as well as the Japanese Atomic Energy Agency (JAEA) and the International Atomic Energy Agency (IAEA), particularly those relating to response following Fukushima and Chernobyl. Commercial vendor reports were considered and included in the survey if data and claims made were reasonable and tests were carried out appropriately. Often commercial vendors/manufacturers perform product testing in collaboration with other research agencies. Finally, data available on commercial websites and community websites were searched for relevant information, although this information should carry minimal weight in analyzing technology gaps.

Since the determination of technical gaps for containment technologies was evaluated, the assurance of data quality in source documents was not evaluated beyond that which a journal article peer- reviewer would perform. No data reduction was required for the development of a technical gap analysis.

6.2 Laboratory Testing of Stabilization Technologies

The quantitative evaluation of Cs-137 interaction and dose attenuation is described in Section 3 of this report and the work was performed according to a QAPP (Sutton, 2014b). The experimental objective was to address technical gaps associated with promising stabilization technologies for RDD and IND contamination, applied before decontamination to prevent resuspension and minimize dose, as follows:

- Impacts of selected stabilization technologies on ultimate decontamination and waste management strategies;
- Dose attenuation of selected stabilization technology;
- Interaction and solubility of Cs-137 with stabilization technologies;

- Effectiveness of selected stabilization technology to prevent resuspension during disturbance mechanisms;
- Long-term stability and effectiveness of selected stabilization technology over time.

Critical measurements that were required to fulfill these objectives included:

- Temperature during testing;
- The mass of liquids and solids used in each experiment;
- The purity of reagents used in each experiment;
- The uniformity (homogeneity) of each of material tested;
- The volume of liquid used in each experiment;
- The amount of Cs-137 at the beginning and end of each experiment;
- The amount of radioactivity bound to solid material;
- The amount of radiation and dose exiting a layer of stabilization material;
- The collection and analysis of particles used in outdoor field experiments;
- The time taken for stabilization technologies to degrade in outdoor field experiments.

Data quality indicators for the critical measurements will be used to determine if the collected data meet the quality assurance objectives. A list of these data quality indicators can be found in Table 6-1.

Table 6-1. Data quality indicators for critical measurements

Measurement Parameter	Analysis Method	Accuracy	Precision/ Repeatability	Detection Limit	Completeness %
Temperature	Temperature probes	± 1^{o}C	2 %	0.0 ^{o}C	90
Supernatant volume and solid mass	Mass balance	± 2 %	2 %	N/A	100
Activity in supernatant / eluent	Gamma spec / gamma counting	± 2 %	± 2 %	Cs-137: $5.5x10^{-3}$pCi	95
Activity emanating through stabilization layer	Hand-held dose and rate meters	± 2 %	± 2 %	Unknown	100

An additional set of quality indicators is applied to the laboratory blanks, positive controls, and test coupons. These quality indicators are listed in Table 6-2. The equipment used to make the critical measurements was calibrated according to Table 6-3.

Table 6-2. Additional data quality indicators specific to the test matrix samples

Coupon Type	Data Quality Indicator	Corrective Action
Blank samples	Above natural background	If value is significant and consistent then use value as background. If value is high in a small number of samples, investigate possible sources of cross contamination.

Table 6-3. Equipment calibration schedule

Equipment	Responsible Group	Frequency
Temperature sensor	Manufacturer	Annual
Mass balance	Laboratory Personnel	Annual
HPGe detector	Laboratory Personnel	Annual / 90-days
Hand-held dose and survey meters	Laboratory ES&H Tech	Annual

Measures that demonstrate whether the data meet quality assurance objectives include the precision, accuracy, and completeness of the collected data. These measures are defined below. Precision describes the closeness of data, obtained using the same procedure. There are three functions that are used to describe precision: standard deviation, variance, and coefficient of variance. The precision of a data set can be defined using the following equation:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \mu)^2}{N}}$$

where
N = the number of replicates in the data set
x_i = the measured value in the data set
μ = the data set mean.

When applied to a smaller data set, a sample standard deviation is calculated changing the equation to the following:

$$s = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N-1}}$$

where
s = the sample standard deviation
x = the mean of the smaller data set.

The variance is simply the square of the standard deviation and the coefficient of variance is the standard deviation divided by the mean of the data set, multiplied by 100.

Accuracy describes the closeness of the data to the true value. There are two functions frequently used to describe accuracy: absolute and relative error. Absolute error is the measured value minus the actual value, while the percent relative error is the same difference divided by the actual value and multiplied by 100.

The percent completeness of the data is simply the ratio of the number of data points taken to the total number of data points planned, multiplied by 100.

Ortec HPGe detectors were used to measure Cs-137 in aqueous samples from sorption experiments. The detectors were calibrated against NIST certified isotopic standards, plus additional quality control checks during routine operation as follows:

- The efficiency and energy calibrations of the gamma counters are checked routinely using NIST-traceable sources.
- Seven day background - every 90 days
- Calibration efficiency check - every 30 days
- Calibration energy & near source check - every 30 days
- Calibration far source check - every 30 days
- Calibration near environmental source - every 60 days

A hand-held Victoreen 451B survey-meter and a Ludlum *Model 12* rate-meter were used to measure dose and count rate attenuation through a variety of thicknesses, and were calibrated against certified isotopic standards, plus additional quality control checks during routine operation as follows:

- Background checks - before and after each measurement of samples
- Calibration efficiency check – daily, start and end of day
- Battery check – daily, start and end of day
- Physical integrity – daily, start and end of day

A qualitative outdoor demonstration of stabilization technologies during driving and walking activities is documented in Section 4 of this report and a subsequent semi-quantitative study is documented in Section 5.

Both blank and positive control were included in the test matrix to determine background values and the relative effect of stabilization technologies in each of the experimental studies described in Sections 3, 4 and 5 – Cs-137 dose reduction, Cs-137 absorption, and indoor/outdoor testing using simulated contamination. Additional information on control samples, replicates and results are presented in individual sections.

7. Waste Management and Decontamination Considerations

Waste management information can be extracted from the product safety data sheets in relation to intended application. However, when used for radiological stabilization, additional waste management considerations must be considered. Additionally, the impact the material has on subsequent decontamination must be considered.

All three stabilization technologies tested in this work dry over time, so the majority of waste will be solid (containing some water content). If physically removed from surfaces in the applied form, solid waste will be similar in mass to the material applied plus the content of residual water and accounting for removal of all of the material deposited. Alternatively, the material can be washed off surfaces resulting in a mixture of mostly liquid waste with some residue remaining. Residue from Phos-Chek®MVP-F fire retardant and Soil$_2$O® will be greater than that for $CaCl_2$, which can be completely dissolved. Information on the "normal" (non-radioactive) *waste* generated from each technology was collected from the product material safety data sheets (MSDS) and product websites. The MSDS information for each product is provided in Appendix D.

> **Phos-Chek®MVP-F <u>fire retardant:</u> "**This material when discarded is not a hazardous waste as that term is defined by the Resource, Conservation and Recovery Act (RCRA), 40 CFR 261. Dry material may be landfilled or recycled in accordance with local, state and federal regulations. Consult your attorney or appropriate regulatory officials for information on such disposal" (Phos-Chek®MVP-F).
>
> **Soil$_2$O® <u>wetting agent:</u>** "In concentrate form, this product is a non-hazardous waste material suitable for approved solid waste landfills. Diluted product is non-soluble and can be disposed of in suitable effluent treatment plants. Dispose of contents/container in accordance with local/regional/national/international regulations" (Soil2O MSDS)
>
> **<u>$CaCl_2$ salt:</u>** "This material, as supplied, is not a hazardous waste according to Federal regulations (40 CFR 261). This material could become a hazardous waste if it is mixed with or otherwise comes in contact with a hazardous waste, if chemical additions are made to this material, or if the material is processed or otherwise altered. Consult 40 CFR 261 to determine whether the altered material is a hazardous waste or local regulations for additional requirements" ($CaCl_2$ MSDS).

Since each technology is considered non-hazardous, the addition of radioactive material should not result in mixed waste.

The *environmental* impact is also an important consideration in selecting and using each of the stabilization technologies. The following information was obtained from the product safety data sheets:

> **Phos-Chek®MVP-F <u>fire retardant:</u>** "Coldwater fish: 96-hr lethal concentration 50% (LC50). Rainbow trout: 1845 mg/L, practically nontoxic" (Phos-Chek®MVP-F)
>
> **Soil$_2$O® <u>wetting agent:</u>** "No negative or toxic effects on the environment are anticipated when released in dilution for terrestrial and aquatic ecosystems; based on government

testing. Composted polyacrylate polymers are nontoxic to aquatic or terrestrial organisms at predicted exposure levels from current application rates. Decomposes over time or in the presence of natural sunlight when applied to terrestrial substrate or vegetation. Polyacrylate polymers are relatively inert in aerobic and anaerobic conditions. They are immobile in landfills and soil systems (>90% retention), with the mobile fraction showing biodegradability. They are also compatible with incineration of municipal solid waste. Incidental down-the-drain disposal of small quantities of polyacrylic polymers will not affect the performance of wastewater treatment systems" (Soil2O MSDS).

$CaCl_2$ salt: "This product does not contain any substances regulated as pollutants pursuant to the Clean Water Act (40 CFR 122.21 and 40 CFR 122.42). This material, as supplied, does not contain any substances regulated as hazardous substances under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) (40 CFR 302) or the Superfund Amendments and Reauthorization Act (SARA) (40 CFR 355). There may be specific reporting requirements at the local, regional, or state level pertaining to releases of this material. It is important to note here that $CaCl_2$ will form corrosive brines that will leach metals from some surfaces" ($CaCl_2$ MSDS).

For $CaCl_2$, application will result in acidic, metal containing solutions that may (when combined with radioactive material) generate mixed waste.

Finally, the impact on the ultimate decontamination process is an important consideration. The selected stabilization technology should not hinder decontamination processes once stakeholders have agreed on the selection of the decontamination.

Experimental testing of Cs-137 with Phos-Chek®MVP-F fire retardant showed the formation of a rubbery material on drying that contained the vast majority of the radioactivity. The material was easily removed from the experimental glassware, suggesting that there would be a positive impact on decontamination (with activity being trapped in the dried fire retardant matrix). It is not known whether similar results would be achieved on different surfaces such as asphalt or concrete.

Experimental testing of $Soil_2O$® wetting agent showed that on drying, solid chips were formed that adhered to the glass surface. When removed, these particles contained much of the activity added to the experiment, but significant effort was required to pry the particles away from the surface. This suggests that in the dry form, the $Soil_2O$® may have negative implications for subsequent decontamination, but it does appear that maintaining some level of moisture in the $Soil_2O$® product would prevent the formation of chips and aid in the removal of radioactive contamination. This could be accomplished by rewetting the $Soil_2O$® periodically to maintain desired properties.

Similarly, $CaCl_2$ dries to form solid chips that also contain Cs-137, but can be redissolved on the application of water. However, excessive water can lead to complete dissolution of $CaCl_2$ and subsequent migration of Cs-137. It was found in experimental studies that higher concentrations of aqueous $CaCl_2$ aid the sorption properties of Cs-137 on solid material such as Arizona road dust.

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Appendix A: Information on Potential Stabilization Technology Provided to Stakeholders

Technology	Availability & Cost	Additional Labor and Material Requirements	Anticipated Efficacy	Unintended Consequences	Waste Volume	Data Availability
Water application/ fogging nozzle	Most widely available and cheapest technology	Hydrant, hoses, fire truck, run-off collection	Good knock-down of airborne particles; soluble contamination will not be available for reaerosolization unless non-porous surfaces dry out	Solubilize contamination, migration into surfaces, run-off into groundwater and sewer system; fogging may increase aerosol mobility	Potential for large volumes given both water volume and contaminated porous materials	Cloud-seeding after Chernobyl resulted in rainfall that subsequently removed contamination from the atmosphere and deposited on to land
Fire-extinguishers: Carbon dioxide (CO_2); Purple K dry chemical extinguishing agent (potassium bicarbonate)	Widely available; limited volume would require many units; $160 for 20 pound (lb) handheld unit, $900 for 50 lb wheeled unit	None	CO_2 dries to leave no residue – poor efficacy; Dry powder may form barrier to prevent reaerosolization without solubilizing, K competes with Cs for sorption and chemistry	Potential for particle reaerosolization during application	CO_2 – zero Purple K – removed by suction; on wetting, forms thick/crusty, difficult to remove layer	None for rad or particle stabilization
Fire-fighting foam: Wet foam (protein, fluroprotein, aqueous film-forming)	Typically 5 gal/fire-engine; airport depts. have larger quantities ; $180/ 5 gallon (gal) pail	Fire trucks and hoses, proportioning system; run-off collection; airport units may be reserved for airport use and cannot attend unless airport is shut down	Good for a short period of time (solubilizing contamination)	Run-off, high flow; large contamination of sewer system and porous materials possibly resulting in more extensive/expensive decon; fast dissipation time may require reapplication; depends on environmental conditions (wind, RH, temp)	After dissipation, waste volume is approximately the same as the water added; however, volume of contaminated sewer water and porous materials will be large (if contamination enters porous material)	No data available on particle suppression; designed and used for fire suppression
Dry firefighting foam (high expansion, e.g., Hi-Ex, Ultra Foam, Jet X)	Typical fire-engine carries 1 gal; typically used for indoors and wildland pre-treatment; wildland fire units carry more but may not be available immediately depending on location; $95/ 5 gal pail	Fire truck, hoses, proportioning system	Good; longer dissipation time than wet foam; can be applied to vertical surfaces	Run-off, possible contamination of sewer system and porous surfaces; movement through foam (e.g. walking/driving) can destroy foam cover; depends on environmental conditions (e.g. wind, RH, temp)	After dissipation, volume is approximately the same as the water added plus porous materials if dissolution of contamination occurs and contamination enters porous materials; dry uses significantly less water than wet foam	

Table 1. continued…

Technology	Availability & Cost	Additional Labor and Material Requirements	Anticipated Efficacy	Unintended Consequences	Waste Volume	Data Availability
Hazmat materials SDF-200 (in addition to typical foams)	Carried by Hazmat and FEMA task force only	Proportioning system	Good, demonstrated for rad		Volume approximately equal to collapsed foam plus rinsing any solution	
Rad-Specific Acrylics (e.g. InstaCote CC Strip, CC Wet and CC Fix, Bartlett Stripcoat TLC and Polymeric Barrier System, Isotron RADblock, ALARA and IsoFix)	Typically short shelf-life with limited quantities on-hand with lead-time of ~ 1 week; \$400-500/ 5 gal; typically <\$1/ sq-ft	Sprayer	Demonstrated, very good; some products appropriate for vertical surfaces	Typically 18-24 hour cure time. At a 2015 demonstration (after this table was provided to stakeholders), it was shown that some coatings could not be removed from building walls.	Small and limited to the amount of material applied	Demonstrated in nuclear installations and experimental tests Unlikely to be available locally. Specific logistics and training required for application
Rad-Specific Epoxys (e.g. InstaCote CC Epoxy SP, InstaCote M-25 {ML})	Typically limited quantities on-hand with lead time;	Typically require some surface prep	Demonstrated, good; vertical and horizontal surfaces; cures in short period of time	Some compounds are toxic/hazardous – environmental and health concerns	Small and limited to the amount of material applied	Demonstrated in nuclear installations and experimental tests Unlikely to be available locally. Specific logistics and training required for application
Decon Foams (InstaCote Autofroth, Global Metrechs Inc. NuCap, SNL AFC-380 and SF-200, CTRI CASCAD SDF, Dow FrothPak, Celcore GeoFill)	Relatively inexpensive, may require lead-time depending on supply and availability; \$1-10 /cubic ft	Proportioning and delivery system	Good, demonstrated for rad		Volume approximately that of collapsed foam plus any rinse solutions	Demonstrated in nuclear installations and experimental tests Unlikely to be available locally. Specific logistics and training required for application
Cakes (e.g. AGUA A3000)	Long lead-times depending on supply and availability	High-volume spray delivery system	Good, demonstrated for hazardous materials including rad at Fukushima	May be difficult to remove from some surfaces	Possibly larger volumes compared to acrylic and epoxy, limited to the amount of material applied	Demonstrated at Fukushima Unlikely to be available locally. Specific logistics and training required for application
Gels/Polymers (e.g. DeconGel, ANL Supergel, NEI WES Strip)	Long lead-times depending on supply and availability; \$400-500/ 5 gal pail;	Spray system	Good, demonstrated for rad incl. Fukushima	Cure times typically 18-24 hours	Volume approx. same as application volume	Demonstrated in nuclear installations, experimental tests and at Fukushima Unlikely to be available locally. Specific logistics and training required for application

Table 1. continued…

Technology	Availability & Cost	Additional Labor and Material Requirements	Anticipated Efficacy	Unintended Consequences	Waste Volume	Data Availability
Mulch	Routinely used by construction and transit agencies, available from large hardware stores and mulch suppliers; $40-120/ cubic yards (CY) installed	Trucks for transport and equipment for dispersal commonly used by city, county and state landscaping	Good, assuming a layer thickness and maintenance that prevents movement of base layer; much material may also adsorb soluble contamination. Slopes greater than 3:1 usually requires additional treatment such as a tackafier; long fibrous or shredded bark, not chips; 4" mulch depth must be reapplied every 2-3 years (3" 3-4 years)		Approx same volume as applied	Data from Caltrans Roadside Toolbox (http://www.dot.ca.gov/hq/LandArch/roadside/detail-gm.htm) None for radiological contamination
Gravel	Routinely used by construction and transit agencies; available from large hardware stores and gravel suppliers; $10 - $15/yd^2 on flat areas, $11 - $23/yd^2 on slopes	Trucks for transport, equipment for spreading	Good, assuming a layer thickness that prevents resuspension between gravel pieces	Spaces between gravel pieces can allow water infiltration, leading to possible migration of aqueous Cs-137 into subsurface, groundwater and sewer water	Approx same volume as applied	Used in Japan following Fukushima Cost data from Caltrans Roadside Toolbox (http://www.dot.ca.gov/hq/LandArch/roadside/detail-gm.htm)
Imported Soil (non-local, non-contaminated)	1” depth = 140 CY/acre; 3” depth = 420 CY/acre; 6" depth = 840 CY/acre $15-70/CY	Trucks for transport and equipment for dispersal commonly used by city, county and state landscaping	Good; may require wetting to maintain	Infiltrating water may leach contamination	Approx same volume as applied	None for rad
Sand	Cheap material, widely available but typically carried in a 5 gal bucket; obtain large quantities from public works yard; $42-80/CY	Trucks for transport; equipment for spreading; possible wetting to prevent movement	Good; may require wetting to prevent movement from site of application	Potential to clog infrastructure (e.g. surface drains – which may be a positive)	Approx same volume as applied	None for rad

Table 1. continued…

Technology	Availability & Cost	Additional Labor and Material Requirements	Anticipated Efficacy	Unintended Consequences	Waste Volume	Data Availability
Straw	2 tons/A; $8-24/bale (14x18x41")	Trucks for transport and equipment for dispersal commonly used by city, county and state landscaping	Unknown; would require regular maintenance (e.g. wetting)	Infiltrating water may leach contamination; potential to resuspend	Approximately the same volume as applied	http://www.dot.ca.gov/hq/LandArch/ec/hydroseed/punched_straw.htm None for radiological use
Commercial Paint	Cheap material, widely available	Motorized sprayer or vehicle; surfaces should be "clean" before painting	Will provide effective barrier if allowed to cure correctly before mechanical contact	Requires curing, consideration of surface type and aging, hazardous environmental considerations	Once stripped, the volume is approximately the same as that applied.	
Clays (montmorillonite, kaolinite, illite)	Readily available from specialized suppliers; relatively low cost; $8-32/50 lb bag	May also require wetting to prevent cracking	Demonstrated for rad: good. Wet clay swells to form impermeable layer		Volume approx. same as that applied	Krumhansl et al., 2000
Chloride Salts ($CaCl_2$, Magnesium Chloride ($MgCl_2$) w/ or w/o road salt)	Most commonly used dust control agents; 0.27 gal/yd2, $0.66/gal (1983); ~300-600/acre; readily available	Standard city/county public works or state highway truck for distributing on the road	Typically last 6-12 months; Good (55-77%); reapplication 1-2 times a year, good for traffic areas	Environmentally safe; $CaCl_2$ is corrosive to vehicles and application equip.; can create slippery surface; easily leached away; exothermic; $MgCl_2$ requires T>70F, RH>32%		Tawil 1983; also http://epdfiles.engr.wisc.edu/pdf_web_files/tic/bulletins/Bltn_013_DustControl.pdf; most common road dirt stabilization; also used at mining sites
Lignin	Untreated material is available for free from wood pulp digestion processes. Dried and processed lignin is not free; 0.37 gal/yd2, $0.1/gal (1983)	Spreading equipment and expertise	Demonstrated for rad including in Ukraine and Belarus following Chernobyl	Untreated material is highly acidic, foul-smelling when spread, and very sticky, clinging to vehicles. Diluted by heavy rains and becomes slippery when wet and very brittle when dry.		Tawil 1983; also http://epdfiles.engr.wisc.edu/pdf_web_files/tic/bulletins/Bltn_013_DustControl.pdf
Road oil	0.4 gal/sq-yd, ~$0.7/gal (1983)	Spreading equipment and expertise	Good, 20-year durability	Difficult removal and cleanup		

Table 1. continued…

Technology	Availability & Cost	Additional Labor and Material Requirements	Anticipated Efficacy	Unintended Consequences	Waste Volume	Data Availability
Dust Wetting Agents (e.g. propylene glycol products)	Low cost; typically available on smaller scale for piles	Hose or spray vehicle	Moderate (30-50%), requires reapplication	Not appropriate for traffic areas	Large volume can be a problem	Used at mining sites
Dust Binding Agents (e.g. lignin, emulsions)	~$750/acre; available on a reasonably large scale	Hose or spray vehicle	Moderate (30-50%); may require reapplication	Leaching of lignin may occur	Brittle when dry, slippery when wet	Used at mining sites
Dust Surface Crusting Agents (e.g. acrylics)	~$700/acre; available on a reasonably large scale; may require 4-6 weeks lead-time beyond supplier stocks	Hose or spray vehicle	Good	May not be appropriate for traffic areas		Used at mining sites
Emulsified Petroleum Resins	~$800-5000/acre; available on a reasonably large scale	Spreading vehicle	Good (50-90%); reapplication 1-2 times a year, suitable for traffic areas	Environmental impacts; difficult to remove		Used at mining sites

Appendix B: ImageJ Macro

```
 dir = getDirectory("Choose a Directory ");
 setBatchMode(true);
 count = 0;
 countFiles(dir);
 n = 0;
 processFiles(dir);
 //print(count+" files processed");
 function countFiles(dir) {
    list = getFileList(dir);
    for (i=0; i<list.length; i++) {
        if (endsWith(list[i], "/"))
            countFiles(""+dir+list[i]);
        else
            count++;
    }
}
 function processFiles(dir) {
    list = getFileList(dir);
    for (i=0; i<list.length; i++) {
        if (endsWith(list[i], "/"))
            processFiles(""+dir+list[i]);
        else {
           showProgress(n++, count);
           path = dir+list[i];
           processFile(path);
        }
    }
}
function processFile(path) {
           setBatchMode("hide");
      if (endsWith(path, ".JPG")) {
          open(path);
                      imgName=getTitle();
                      run("Split Channels");
                      selectWindow(imgName + " (blue)");
                      close();
                      selectWindow(imgName + " (red)");
                      close();
setBatchMode("show");
                      selectWindow(imgName + " (green)");
          run("Subtract Background...", "rolling=50 black");
                      setAutoThreshold("Default");
                      //run("Threshold...");
                      setThreshold(0, 35);
                      setOption("BlackBackground", false);
                      run("Convert to Mask");
                      run("Make Binary");
//Measure only in a ROI to avoid including label
```

```
			minX = 700;
			minY = 1000;
			maxX = 2500;
			maxY = 2500;
			makeRectangle(minX,minY,maxX-minX,maxY-minY);
	//save(path);
			run("Measure");
			row = nResults-1;
			setResult("Label",row,imgName);
			roiArea = (maxX-minX)*(maxY-minY);
			setResult("roiArea",row,roiArea);
// close();
			//close();
	}
  }
```

Appendix C: Information Table for Stabilization Technologies

Stabilization	
Objective	Temporary binding of particulate contamination to minimize migration and resuspension, providing reduction in both surface dose rate and inhalation risk to workers within the first 48-72 hours. Technologies differ from traditional fixatives and strippable coatings in that large amounts of material can be made available and deployed early in the response phase.
Other benefits	Provides stakeholders with additional time to prioritize and plan decontamination efforts, controls the contaminated area.
Management option description	Locally available, non-traditional stabilization technologies can be obtained quickly and applied easily using pre-existing methods. Such technologies do not require specialized equipment or operator knowledge. Three examples of such materials include: (a) fire retardant, (b) dust wetting agents, and (c) chloride salt road stabilizers. **Fire retardants:** Phosphate-based material, thickened with either guar gum or clay can be applied via a range of methods, from hand or backpack sprayer for smaller areas, fire-truck and hose for local areas, to aerial drop via plane or helicopter for wide area application. Research is needed to determine whether turbulence from aerial drop or fire-truck applications would result in resuspension of particles. Available in a range of viscosities in both powder and pre-mixed liquid. Powder:water ratio can be increased to increase viscosity, aiding application on non-horizontal surfaces such as roofing and walls. Red colorant allows easy identification of treated areas. Provides dose reduction. Surface layer prevents resuspension. **Dust wetting agents:** Used in dust suppression for mining and soil operations, can be applied via a range of methods, from hand/backpack sprayer for smaller areas, truck sprayer for roads, and hose for non-horizontal surfaces. Available from a variety of suppliers, mixed with water to desired viscosity. Provides dose reduction, and surface layer prevents resuspension. **Chloride salt road stabilizers:** Commonly used to stabilize dirt and gravel roads, can be applied via a range of methods, from hand/backpack sprayer for smaller areas, truck sprayer for roads, or hose. Dries to form crust, preventing resuspension. Aids in the binding of Cs-137 to surfaces. Further wetting (rain or hose) can resolubilize chloride crust. **Walls:** Most practical stabilization material for walls is high-viscosity fire retardant, will adhere to vertical surfaces. Application may vary from individual wall application and hose application to aerial with diagonal deposition. **Roofs:** Similar to walls, most practical stabilization material for roofs is high-viscosity fire retardant. May also use higher viscosity mixture of dust wetting agent. Application may vary from individual roof application and hose application to aerial deposition. **Roads and paved areas:** All three technologies may be applied to roads and paved areas. Prevention of resuspension from traffic highest with fire retardant, and also appreciable with wetting agent and chloride salt application. **Open spaces, parks, forests, and vegetation:** All three technologies may be applied to areas containing soil and vegetation.

Stabilization (continued)	
Target	Contaminated external walls and roofs of buildings, outdoor surfaces ranging from paved roads and dirt roads to vegetation. May also be applied to semi-enclosed areas and vehicles but may cause corrosion on metal surfaces. It may be beneficial to give particular focus to schools, kindergartens, hospitals and other buildings frequented by large numbers of people.
Targeted radionuclides	All long-lived radionuclides (half-life greater than expected time to reoccupancy or recovery time). Short lived radionuclides (half-life less than expected reoccupancy/recovery time) only if implemented quickly. Demonstrated with Cs-137, which is highly soluble.
Scale of application	Any size.
Time of application	Maximum benefit if carried out soon after deposition (within 24-72 hours) when maximum contamination is still on the surfaces. As time passes before stabilization, the amount of resuspension will likely increase given disturbances across the surfaces on which particles have deposited. Early application will minimize resuspension, reduce surface dose rates, reduce inhalation dose and reduce the expansion of the contaminated area.
Constraints	
Legal constraints	Liabilities for possible damage to property (e.g., corrosion). Ownership and access to property. Disposal of contaminated water / run-off via public sewer system. Use on listed and other historical buildings, or in conservation areas.
Environmental constraints	Severe cold weather (snow and ice may cause problems and water mixtures would need to be heated). Fire retardants may pose danger to fish.
Effectiveness	
Reduction in contamination migration from surfaces	The stabilization achieved depends on the type of application, weathering. A higher degree of stabilization will be achieved if there has been minimal surface disturbance before application. Disturbances may be natural (wind, rain) or anthropogenic (driving, walking). Laboratory testing and outdoor field-testing shows cesium-137 and surrogate particulate contamination trapped on surfaces, thus minimizing resuspension from natural and anthropogenic turbulent mechanisms. However, rain appears to be detrimental to effectiveness. Repeated application or wetting required for chloride salts.
Reduction in surface dose rates	External gamma and beta dose rates from surfaces are attenuated by both fire retardant and wetting agent stabilization technologies. A 1-inch thickness of fire retardant can provide a 25x reduction in dose rates. It is believed that the dose rate attenuation is due to the water content of both the fire retardant and the wetting agent. Drying of these materials yields an increase in dose rate, but does fully return to an unshielded level.
Reduction in resuspension	Resuspended activity in air following application of stabilization technologies may be significantly reduced. Of the three materials tested, fire retardant may offer the greatest reduction in transfer. As a result, a reduction in the inhalation dose may be expected, as may a reduction in the transfer of contamination, minimizing the growth of the contaminated area from the original source term.

Stabilization (continued)	
Technical factors influencing effectiveness	Method used – sprayer, hose, aerial drop, mixture ratio, viscosity, thickness, pressure/force used during application. Application method will affect coverage and accuracy of deposition. Aerial drop will apply materials over a wider area that hose or sprayer, but will result in less accurate application and lacks the ground-based observations during application to know if enough (or too much) material has been applied to the relevant surfaces. Environmental conditions and effects (e.g., drying or runoff). Drying will reduce dose attenuation (from beta emissions) for fire retardant and wetting agent. Drying will also lead to cracking of chlorides. Chlorides may require periodic rewetting to maintain effectiveness. Rain events may cause runoff of fire retardant and excessive rain may cause dissolution and runoff of chloride technology. Surface type and orientation – rough horizontal surfaces are more amenable to chloride stabilization, while vertical surfaces and rooftops may require more viscous technologies such as high-viscosity fire retardant. Time of implementation: the longer the time between deposition and implementation of the option, the less effective it may be due to stabilizing the contamination on surfaces and the wider the area requiring stabilization given resuspension prior to implementation.
Social factors influencing effectiveness	N/A
Feasibility	
Equipment	Equipment needed to disperse stabilization technology material depends on scale of application, from backpack sprayer for small, localized areas to fire-trucks, sprayer trucks, helicopter and airplane. Chloride salts and wetting agents require water. Dry fire-retardant requires water, although retardant can be purchased in pre-mixed formulation. Sprayer trucks can be used for chloride salt solutions and wetting agents, commonly applied by public works and highway agencies. Fire-truck application requires eductor and mixing equipment. Aerial application requires mixing equipment and transportation vessel. For aerial application, wild-fire department equipment could be utilized.
Utilities and infrastructure	Roads for transport of equipment. Water and power supplies. Runway/airport for aerial deployment.
Consumables	Fuel and parts for generators and transport vehicles. Water. Calcium chloride, wetting agent or fire retardant.
Skills	Personnel skilled in the use of sprayer trucks, backpack sprayers, fire-department fire-truck operation and aerial application (pilots for helicopter and airplanes). These skills could be found readily through public works, state highway agencies, fire departments and wildland fire departments.
Safety precautions	Water-resistant clothing will be required, particularly in highly contaminated areas. Personal protective equipment (PPE) will be required, including respiratory protection, to protect workers contamination before and during application of stabilization technologies. Clear airspace for aerial drop application. Limited access for people on the ground immediately before aerial drop. For tall buildings: OSHA-required fall-protection and safety helmets.

Stabilization (continued)	
Waste	
Amount	All three stabilization technologies dry over time, so the majority of waste will be solid (containing some water content). Solid waste will be similar in mass and volume to the material applied (accounting for recovery efficiency) due to wet application followed by evaporation/drying reducing mass and volume and collection of surface materials increasing volume. Alternatively, the material can be washed off surfaces. Disposal will be subject to conditions depending on the activity levels and other properties of waste.
Type	Fire retardant residue, wetting agent residue, chloride salts, water. The following applies only to the material as supplied by the manufacturer and may differ with the presence of radionuclides. **Fire retardant:** This material when discarded is not a hazardous waste as that term is defined by the Resource, Conservation and Recovery Act (RCRA), 40 CFR 261. Dry material may be landfilled or recycled in accordance with local, state and federal regulations. Consult your attorney or appropriate regulatory officials for disposal information on such disposal. (Phos-Chek®MVP-F MSDS). **Wetting agent:** In concentrate form, this product is a non-hazardous waste material suitable for approved solid waste landfills. Diluted product is non-soluble and can be disposed of in suitable effluent treatment plants. Dispose of contents/container in accordance with local/regional/national/international regulations. (Soil2O MSDS) **Chloride salt:** This material, as supplied, is not a hazardous waste according to Federal regulations (40 CFR 261). This material could become a hazardous waste if it is mixed with or otherwise comes in contact with a hazardous waste, if chemical additions are made to this material, or if the material is processed or otherwise altered. Consult 40 CFR 261 to determine whether the altered material is a hazardous waste. or local regulations for additional requirements. ($CaCl_2$ MSDS).
Dose rates	
Averted dose rates	Estimated dose rate reductions are typically up to 25x reduction as demonstrated by fire retardant but may vary with a number of factors such as weathering and amount and type of other natural and anthropogenic disturbances.
Factors influencing averted dose rate	Consistency in effective implementation of option over a large area, including thickness, viscosity and drying rate. Population behavior in the area. Number of buildings.
Additional Exposures	Relevant exposure pathways for workers are: - external exposure from radionuclides in the environment and contaminated equipment - inhalation of radioactive material resuspended from the ground and other surfaces (may be enhanced over normal levels) - inhalation of dust - *inadvertent ingestion of dust from workers' hands* Contributions from pathways in italics will not be significant and doses from these pathways might be controlled by using PPE and good safety and housekeeping practices. Exposure routes from transport and disposal of waste are not included. No illustrative doses are provided as they will be very specific to the type of contamination, environmental conditions, the tasks undertaken by an individual, controls placed on working and the use of PPE.

Stabilization (continued)		
Intervention costs		
Material Cost	Specific equipment Specific supplies	Equipment already available, cost will be labor and fuel **Fire retardant:** $125 / 50 gal, product is often sold in bulk (2000 lb) units. **Wetting agents:** $108 for a 15 lb pail, 45 lb of product is mixed with 2000 gal water to treat an area of 80,000 sq ft, a maintenance load at 1/3 strength is applied approx. 1x per week **Chloride salts:** $16 for a 50 lb bag, product is often sold in bulk units, 0.5 - 1.0 kg/ sq m, applied as dry flake; 0.9 - 1.6 l/sq m liquid application. For unpaved road dust suppression, product is reapplied 1-2 times per season
Operator time	Work rate (m^2/hr per team)	Backpack sprayer: 10 - 30 Fire truck: 70 for roofs, 600-700 for walls, 1000 for roads Sprayer truck or aerial drop: depends on vehicle, deposition rate, desired consistency and minimization of resuspension on impact. Depending on the PPE used individuals may need to work restricted shifts.
	Team size (people)	Depends on the method of application. For backpack sprayer and fire-truck, typically 2-3, possibly up to 5, will depend on equipment used and access to buildings. Sprayer truck typically 1-2 people. Aerial application typically 3 people.
Factors influencing costs	Weather. Size of areas to be treated. Topography of area when treating roads and paved areas. Type of equipment used. Access. Use of personal protective equipment (PPE).	

Stabilization (continued)

Side effects	
Environmental impact	The following applies only to the material as supplied by the manufacturer and may differ with the presence of radionuclides. **Fire retardant:** Coldwater fish: 96-hr LC50 Rainbow trout: 1845 mg/L, Practically Nontoxic (Phos-Chek®MVP-F MSDS). **Wetting agent:** No negative or toxic effects on the environment are anticipated when released in dilution for terrestrial and aquatic ecosystems; based on government testing. Composted polyacrylate polymers are nontoxic to aquatic or terrestrial organisms at predicted exposure levels from current application rates. Decomposes over time or in the presence of natural sunlight when applied to terrestrial substrate or vegetation. Polyacrylate polymers are relatively inert in aerobic and anaerobic conditions. They are immobile in landfills and soil systems (>90% retention), with the mobile fraction showing biodegradability. They are also compatible with incineration of municipal solid waste. Incidental down-the-drain disposal of small quantities of polyacrylic polymers will not affect the performance of wastewater treatment systems. (Soil2O MSDS). **Chloride salt:** This product does not contain any substances regulated as pollutants pursuant to the Clean Water Act (40 CFR 122.21 and 40 CFR 122.42). This material, as supplied, does not contain any substances regulated as hazardous substances under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) (40 CFR 302) or the Superfund Amendments and Reauthorization Act (SARA) (40 CFR 355). There may be specific reporting requirements at the local, regional, or state level pertaining to releases of this material. ($CaCl_2$ MSDS).
Social impact	Acceptability of stabilizing contamination rather than removing and disposing of contamination.
Practical experience	Small-scale test on the treatment of roads and paved areas have been conducted in Denmark and the USA under varying conditions. Used following the incident in Goiania. The only practical experience so far has been the study at LLNL for the selected stabilization technologies. Non-radioactive stabilization is the objective of wetting agent and chloride salt – both have been widely demonstrated in road and soil stabilization. Fire-retardant application has been demonstrated widely to provide fire-break in wildland fires, but have not been previously demonstrated for radiological stabilization.

Appendix D: Product Material Safety Data Sheets

ICL Performance Products LP

Material Safety Data Sheet

RESPONSIBLE CARE®
OUR COMMITMENT TO SUSTAINABILITY

1. CHEMICAL PRODUCT AND COMPANY IDENTIFICATION

Product Name:	PHOS-CHEK® MVP-F
Reference Number:	AST10176
Date:	April 27, 2012

Company Information:

ICL PERFORMANCE PRODUCTS LP
622 Emerson Road - Suite 500
St. Louis, Missouri 63141

Emergency telephone: In USA call CHEMTREC: 1 800 424 9300

Outside the USA, including ships at sea, call CHEMTREC's international and maritime telephone number (collect calls accepted):
+1 (703) 527-3887

In Canada call CANUTEC: 1 613 996 6666

General Information: +1 800 424 6169 (Worldwide)

2. COMPOSITION/INFORMATION ON INGREDIENTS

Component	CAS No.	% w/w
Monoammonium Phosphate	7722-76-1	75-85
Diammonium Phosphate	7783-28-0	8-12
Performance Additives+	Trade Secret	< 15

+ Components are Company Trade Secret - Business Confidential. ICL Performance Products LP is withholding the specific chemical identity under provision of the OSHA Hazard Communication Rule Trade Secrets (1910.1200(i)(1)). The specific chemical identity will be made available to health professionals in accordance with 29 CFR 1910.1200 (i)(1) (2) (3) (4)..

3. HAZARDS IDENTIFICATION

EMERGENCY OVERVIEW

Appearance and Odor: Reddish colored mixture of powdered and granular components with little or no odor.

WARNING STATEMENTS

CAUTION
CONTAINS MATERIAL WHICH MAY CAUSE RESPIRATORY TRACT IRRITATION

POTENTIAL HEALTH EFFECTS

Likely Routes of Exposure: Skin contact and dust inhalation

EYE CONTACT: This product is minimally irritating

SKIN CONTACT: This product is no more than slightly toxic.

INHALATION: May cause nasal and respiratory tract irritation based on toxicity information of components.

INGESTION: Practically non toxic. No significant adverse health effects are expected to develop if only small amounts (less than a mouthful) are swallowed.

Refer to Section 11 for toxicological information.

4. FIRST AID MEASURES

IF IN EYES OR ON SKIN, immediate first aid is not likely to be required. However, this material can be removed with water. Remove material from eyes, skin and clothing. Wash heavily contaminated clothing before reuse.

IF INHALED, remove to fresh air. If breathing, immediate first aid is not likely to be required. If breathing is difficult, give oxygen. If not breathing give artificial respiration. Get medical attention.

IF SWALLOWED, immediate first aid is not likely to be required. A physician or Poison Control Center can be contacted for advice.

5. FIRE FIGHTING MEASURES

FLASH POINT: Not combustible

HAZARDOUS PRODUCTS OF COMBUSTION: Not applicable

EXTINGUISHING MEDIA: Not applicable

UNUSUAL FIRE AND EXPLOSION HAZARDS: None known

FIRE FIGHTING EQUIPMENT: Not applicable

6. ACCIDENTAL RELEASE MEASURES

In case of spill, sweep, scoop or vacuum and remove. Flush residual spill area with water.

Refer to Section 13 for disposal information and Sections 14 and 15 for reportable quantity information.

7. HANDLING AND STORAGE

HANDLING

Avoid breathing dust. Keep container closed. Use with adequate ventilation.

Emptied container retains dust and product residue. Observe all labeled safeguards until container is cleaned, reconditioned, or destroyed. The reuse of this material's container for nonindustrial purposes is prohibited and any reuse must be in consideration of the data provided in the MSDS.

STORAGE: Product is stable under normal conditions of storage and handling.

8. EXPOSURE CONTROLS/PERSONAL PROTECTION

EYE PROTECTION: This product does not cause significant eye irritation or eye toxicity requiring special protection. Use good industrial practice to avoid eye contact.

SKIN PROTECTION: Although this product does not present a significant skin concern, minimize skin contamination by following good industrial practice. Wearing protective gloves is recommended. Wash hands and contaminated skin thoroughly after handling.

RESPIRATORY PROTECTION: Avoid breathing dust. Use NIOSH/MSHA approved respiratory protection equipment when airborne exposure is excessive. Consult respirator manufacturer to determine appropriate type equipment for given application. Observe respirator use limitations specified by NIOSH/MSHA or the manufacturer. Respiratory protection programs must comply with 29 CFR 1910.134.

VENTILATION: Provide natural or mechanical ventilation to minimize exposure. If practical, use local mechanical exhaust ventilation at sources of air contamination such as open process equipment.

AIRBORNE EXPOSURE LIMITS:

OSHA and ACGIH have not established specific exposure limits for this material. However, OSHA and ACGIH have established limits for particulates not otherwise classified (PNOC) which are the least stringent exposure limits applicable to dusts.

OSHA PEL	ACGIH TLV
15 mg/m^3 (total dust) 8-hr TWA	10 mg/m^3 (inhalable) 8-hr TWA
5 mg/m^3 (respirable) 8-hr TWA	3 mg/m^3 (respirable) 8-hr TWA

Components referred to herein may be regulated by specific Canadian provincial legislation. Please refer to exposure limits legislated for the province in which the substance will be used.

9. PHYSICAL AND CHEMICAL PROPERTIES

Appearance:	Reddish powder
Odor:	Essentially odorless
Viscosity:	401-800 centipoise @ 21 °C (70 °F) when dissolved in water at the recommended level of 0.95 lbs./gal. of water.
pH:	5.0-6.0

NOTE: These physical data are typical values based on material tested but may vary from sample to sample. Typical values should not be construed as a guaranteed analysis of any specific lot or as specifications for the product.

10. STABILITY AND REACTIVITY

STABILITY: Product is stable under normal conditions of storage and handling.

MATERIALS TO AVOID: None known

HAZARDOUS DECOMPOSITION PRODUCTS: Ammonia and phosphoric acid may be formed when these products are heated above 90 °C (194 °F).

HAZARDOUS POLYMERIZATION: Does not occur.

11. TOXICOLOGICAL INFORMATION

Oral - rat LD50: > 5,050 mg/kg practically nontoxic
Dermal - rabbit LD50: > 2,020 mg/kg; No More Than Slightly Toxic
Eye Irritation - rabbit: 4/110.0; minimally irritating
Skin Irritation - rabbit: 0.0/8.0 (24-hr. exp.); nonirritating

12. ECOLOGICAL INFORMATION

Coldwater fish: 96-hr LC_{50} Rainbow trout: 1845 mg/L, Practically Nontoxic

13. DISPOSAL CONSIDERATIONS

This material when discarded is not a hazardous waste as that term is defined by the Resource, Conservation and Recovery Act (RCRA), 40 CFR 261. Dry material may be landfilled or recycled in accordance with local, state and federal regulations. Consult your attorney or appropriate regulatory officials for information on such disposal.

14. TRANSPORT INFORMATION

The data provided in this section is for information only. Please apply the appropriate regulations to properly classify your shipment for transportation.

US DOT: Not regulated for transportation
Canadian TDG: Not regulated for transportation

15. REGULATORY INFORMATION

TSCA Inventory: All Components Listed
DSL Inventory: Listed
WHMIS Classification: Not Controlled

SARA Hazard Notification
Hazard Categories Under Title III Rules (40 CFR 370): Not Applicable
Section 302 Extremely Hazardous Substances: Not Applicable
Section 313 Toxic Chemical(s): Not Applicable

CERCLA Reportable Quantity: Not applicable

This product has been classified in accordance with the hazard criteria of the Canadian Controlled Products Regulation and the MSDS contains all the information required by the Canadian Controlled Products Regulation.

Refer to Section 11 for OSHA/HPA Hazardous Chemical(s) and Section 13 for RCRA classification.

16. OTHER INFORMATION

	Health	Fire	Reactivity	Additional Information
Suggested NFPA Rating	1	1	0	
Suggested HMIS Rating	1	1	0	E

Reason for revision: New Product Supersedes MSDS dated: n/a
Product Use: Fire Retardant

Phos-Chek ® is a registered trademark of ICL Performance Products LP.
Responsible Care ® is a registered trademark of the American Chemistry Council.

AST10176. doc

ements, including precautionary statements a physician.

WPS-TET-012 - Calcium Chloride Solution

torage

WPS-TET-012 - Calcium Chloride Solution

No data available

WPS-TET-012 - Calcium Chloride Solution

ed as a carcinogen.

g requirements of the Act and Title 40 of the Code of Federal Regulations, Part 372.

in combination with any other material or in any process, unless specified in the text.

Soil2O Dust Control
Safety Data Sheet

SECTION 1: Identification of the substance/mixture and of the company/undertaking

1.1. Product identifier

Product name : Soil2O Dust Control

1.2. Relevant identified uses of the substance or mixture and uses advised against

Use of the substance/mixture : Dust Control Agent

1.3. Details of the supplier of the safety data sheet

GelTech Solutions
1460 Park Lane S, Suite 1
Jupiter, FL 33458
T 561-427-6144 - F 561-427-6182

1.4. Emergency telephone number

T 561-427-6144 - F 561-427-6182

Toll Free: 1-800-924-4874

SECTION 2: Hazards identification

2.1. Classification of the substance or mixture

Classification (GHS-US)

Eye Irrit. 2B H320

2.2. Label elements

GHS-US labeling

Hazard pictograms (GHS-US) : None

Signal word (GHS-US) : Warning

Hazard statements (GHS-US) : H320 - Causes eye irritation

Precautionary statements (GHS-US) : P264 - Wash thoroughly after handling
P305 + P351 + P338 - If in eyes: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing
P337 + P313 - If eye irritation persists: Get medical advice/attention

2.3. Other hazards

No additional information available

2.4. Unknown acute toxicity (GHS-US)

No data available

SECTION 3: Composition/information on ingredients

3.1. Substance

Not applicable

3.2. Mixture

Name	Product identifier	Classification (GHS-US)
Polyacrylate Polymer	(CAS No) Trade Secret	Eye Irrit. 2B, H320
Water	(CAS No) 7732-18-5	Not classified

SECTION 4: First aid measures

4.1. Description of first aid measures

First-aid measures after inhalation : Remove to fresh air and remove material from affected areas. Seek medical advice or attention in the event of any adverse symptoms or irritation.

First-aid measures after skin contact : Wash with water. Seek medical advice if skin irritation develops or persists.

First-aid measures after eye contact : Flush with plenty of water for at least 15 minutes. Seek medical advice if irritation develops or persists.

First-aid measures after ingestion : Immediate first aid is not likely to be required. Seek medical advice or attention in the event of any adverse symptoms.

4.2. Most important symptoms and effects, both acute and delayed

Symptoms/injuries after inhalation	: Exposure to respirable dust may cause respiratory tract and lung irritation and may aggravate existing respiratory conditions.
Symptoms/injuries after skin contact	: Exposure to the dust, such as in manufacturing, may aggravate existing skin conditions due to drying effect.
Symptoms/injuries after eye contact	: Dust may cause burning, drying, itching and other discomfort, resulting in reddening of the eyes.
Symptoms/injuries after ingestion	: Although not a likely route of entry, tests have shown that polyacrylate absorbents are non-toxic if ingested. However, as in any instance of non-food consumption, seek medical attention in the event of any adverse symptoms.

4.3. Indication of any immediate medical attention and special treatment needed

No additional information available

SECTION 5: Firefighting measures

5.1. Extinguishing media

Suitable extinguishing media	: Water. Water spray. Foam. Carbon dioxide (CO2). Dry powder.
Unsuitable extinguishing media	: None.

5.2. Special hazards arising from the substance or mixture

Fire hazard	: None known.
Explosion hazard	: None known.

5.3. Advice for firefighters

Protection during firefighting	: Firefighters should wear full protective gear.

SECTION 6: Accidental release measures

6.1. Personal precautions, protective equipment and emergency procedures

6.1.1. For non-emergency personnel

No additional information available

6.1.2. For emergency responders

No additional information available

6.2. Environmental precautions

Avoid release to the environment.

6.3. Methods and material for containment and cleaning up

For containment	: Stop the flow of material, if this is without risk. Use caution after contact of product with water as slippery conditions may result.
Methods for cleaning up	: Sweep or vacuum material when possible and shovel into a waste container. Dispose of waste in accordance with local, state and federal regulations.

6.4. Reference to other sections

No additional information available

SECTION 7: Handling and storage

7.1. Precautions for safe handling

Precautions for safe handling	: Avoid contact with eyes.

7.2. Conditions for safe storage, including any incompatibilities

Storage conditions	: Store in a dry, closed container.

7.3. Specific end use(s)

No additional information available

SECTION 8: Exposure controls/personal protection

8.1. Control parameters

No additional information available

8.2. Exposure controls

Appropriate engineering controls	: Local exhaust and general ventilation must be adequate to meet exposure standards.
Hand protection	: Use impervious gloves such as neoprene, nitrile, or rubber for hand protection.
Eye protection	: Safety glasses.

Skin and body protection	: Wear suitable working clothes.
Respiratory protection	: If working in a well-ventilated area, none required. If airborne concentrations are above the applicable exposure limits, use NIOSH approved respiratory protection.

SECTION 9: Physical and chemical properties

9.1. Information on basic physical and chemical properties

Physical state	: Solid
Appearance	: Powder
Color	: White
Odor	: None
Odor threshold	: No data available
pH	: 5.5 - 6.5 (1% in water)
Relative evaporation rate (butyl acetate=1)	: No data available
Relative evaporation rate (ether=1)	: < 1
Melting point	: 390 °F
Freezing point	: No data available
Boiling point	: No data available
Flash point	: No data available
Auto-ignition temperature	: No data available
Decomposition temperature	: No data available
Flammability (solid, gas)	: No data available
Vapor pressure	: < 10 mm Hg
Relative vapor density at 20 °C	: No data available
Specific gravity	: 0.4 - 0.7 g/l
Solubility	: Insoluble.
Log Pow	: No data available
Log Kow	: No data available
Viscosity, kinematic	: No data available
Viscosity, dynamic	: No data available
Explosive properties	: No data available
Oxidizing properties	: No data available
Explosive limits	: No data available

9.2. Other information

No additional information available

SECTION 10: Stability and reactivity

10.1. Reactivity

No additional information available

10.2. Chemical stability

The product is stable at normal handling and storage conditions.

10.3. Possibility of hazardous reactions

Will not occur.

10.4. Conditions to avoid

None

10.5. Incompatible materials

None

10.6. Hazardous decomposition products

None known

SECTION 11: Toxicological information

11.1. Information on toxicological effects

Acute toxicity	: Not classified
Skin corrosion/irritation	: Not classified
Serious eye damage/irritation	: Causes eye irritation.
Respiratory or skin sensitization	: Not classified
Germ cell mutagenicity	: Polyacrylate Polymer had no effect in mutagenicity tests.
Carcinogenicity	: Not classified
Reproductive toxicity	: Not classified
Specific target organ toxicity (single exposure)	: Not classified
Specific target organ toxicity (repeated exposure)	: Not classified
Aspiration hazard	: Not classified

SECTION 12: Ecological information

12.1. Toxicity

No negative or toxic effects on the environment are anticipated when released in dilution for terrestrial and aquatic ecosystems; based on government testing. Composted polyacrylate polymers are nontoxic to aquatic or terrestrial organisms at predicted exposure levels from current application rates.

12.2. Persistence and degradability

Decomposes over time or in the presence of natural sunlight when applied to terrestrial substrate or vegetation. Polyacrylate polymers are relatively inert in aerobic and anaerobic conditions. They are immobile in landfills and soil systems (>90% retention), with the mobile fraction showing biodegradability. They are also compatible with incineration of municipal solid waste. Incidental down-the-drain disposal of small quantities of polyacrylic polymers will not affect the performance of wastewater treatment systems.

12.3. Bioaccumulative potential

No additional information available

12.4. Mobility in soil

Polyacrylate polymers are immobile in landfills and soil systems (>90% retention), with the mobile fraction showing biodegradability.

12.5. Other adverse effects

Effect on ozone layer	: No additional information available
Effect on the global warming	: No known ecological damage caused by this product.

SECTION 13: Disposal considerations

13.1. Waste treatment methods

Waste disposal recommendations	: In concentrate form, this product is a non-hazardous waste material suitable for approved solid waste landfills. Diluted product is non-soluble and can be disposed of in suitable effluent treatment plants. Dispose of contents/container in accordance with local/regional/national/international regulations.

SECTION 14: Transport information

In accordance with DOT

Not a dangerous good as defined in transport regulations

SECTION 15: Regulatory information

15.1. US Federal regulations

No additional information available

15.2. US State regulations

No additional information available

SECTION 16: Other information

Full text of H-phrases:

	Eye Irrit. 2B	Eye damage/eye irritation Category 2B
	H320	Causes eye irritation

This information is based on our current knowledge and is intended to describe the product for the purposes of health, safety and environmental requirements only. It should not therefore be construed as guaranteeing any specific property of the product www.riskreactor.com

Rare Earths * Glow Paints * Tracers * UV Dyes * UV & Glow Pigments * Security Inks * Invisible Inks * Black Lights * Service

MATERIAL SAFETY DATA SHEET

Risk Reactor Inc.
2676 South Grand Ave.,
Santa Ana, California 92705
United States of America
Tel: (714) 641-3500 Fax: (714) 641-7100
Email: sales@riskreactor.com

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EFFECTIVE DATE : 3-08-13 SUPERSEDES: 6-6-12

Section One – Identity Information

Trade Name: Simulation Powder
CAS Number: No
Product Type: PDT-06
This product is considered to be a non-hazardous substance under that standard.

Section Two – Hazard Ingredients

Ingredients GAS number % ACGIH-TLV OSHA-PEL
As inert dust (total) 3mg/m3 ACGIN-TLV 3mg/m3 OSHA-PEL

Section Three – Physical Data

Appearance: Light-Yellow Powder/No Order
Melting Point: Dissociates 1200 C
Vapor Pressure: N/AP
Vapor Density: N/AP
Solubility In Water: Negligible(<1%)
Flammability Class: N/AP
Extinguishing Media: Water
Specific Gravity: 4.1
Freezing Point: N/AP
Percent Volatile: N/AP
Evaporation Rate: N/AP
pH (% in water): N/AP
Flash Point: N/AP
Auto-Ignition Temp: N/AP
Fire Fighting Procedure-Special
Fire Fighters should wear self-contained breathing apparatus when fighting chemical fires. Use water spray to cool nearby containers and structures exposed to fire.
Unusual Fire And Explosion Hazards: This product will not burn use appropriate techniques to fight surrounding fire.

Section Four – Reactivity Data

Stability: Stable
Hazardous Polymerization: Will not occur.
Conditions to Avoid: Contact with acids
Hazardous Decomposition Products: Hydrogen Sulfide Gas: Thermal Decomposition may evolve

Section Five – Health Hazard Data

Respiratory Equipment: Local Exhaust/mechanical (general)
Protective Gloves: Plastic or Neoprene
Eye Protection: Chemical Glasses
Ventilation:
Other Protective Equipment: Lab Coat
Threshold Limit value: OSHA, PEL Total Dust 3mg/m3
Primary Routes of Exposure: Inhalation/Ingestion/Skin
OSHA PEL: 3mg/m3
ACGIN TLV: 3mg/m3
Effects of Overexposure: May Cause mechanical Irritation to eyes, skins & mucous membranes
Listed Carcinogen: None

Section Six – Emergency & First Aid Data
Skin: Wash off with soap and water
Eyes: Flush with water for 5minutes
Inhalation: Remove to fresh air
Ingestion: Drink quantities of water and induce vomiting
Section Seven – Toxicology Information
This product is of non-toxic, please contact the manufacturer for further information
Section Eight – Spill or Leak Procedures
Spill Procedures: Wear appropriate protective equipment avoid the generation of dust, vacuum or shovel material and place in closable containers for disposal
Waste Disposal Methods: Dispose in accordance with state and local regulations
Section Nine – Regulatory Information
SARA 313 Title III
Toxic Substance Control Act (TSCA): All ingredients in this product are listed on the US EPA TSCA Inventory of chemical substances.
Section Ten – Special Precautions for Industrial Use Only
Handling and Storage Information: Store closed in cool dry area when handling wear protective clothing and respiratory protection. Avoid scatter in the air.
Other Precautions: Maintain a schedule of regular housekeeping to ensure cleanliness.
Section Eleven – Addendum
Definitions and Abbreviations: ACHIH = American Conference of Govemmental Industrial Hygienists.
CAS = Chemical Abstract Service Registry Number
EPA= Environmental Protection Agency
N/AP = Not Applicable
N/AV = Not Available
NOISH = National Institute for Occupational Safety and Health
OSHA = Occupational Safety and Health Administration
PEL = Permissible Exposure Limits.
SARA = Superfund Amendments, hazard categories: Immediate health hazard

SCIENCE

United States
Environmental Protection
Agency

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